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Edge Tones

ARTHUR TABER JONES
Department of Physics, Smith College, Northampton, Massachusetts
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Edge tones are produced when wind from a slit strikes an opposed edge under suitable conditions. Two types of such tones are here distinguished. The first type is the one that has hitherto been most investigated. In it a gradual change of either wind pressure or distance from slit to edge gives several "stages" of tone, in each of which the pitch changes gradually, separated by sudden "jumps" from one pitch to another. The second type occurs at higher pressures, where the sheet of air that escapes from the slit is probably turbulent, and in this type the jumps in pitch are absent. In the first type the ranges of pitch between jumps are never much in excess of an octave, whereas in the second type there may be a continuous range over several octaves. Most of the tones now investigated were obtained with a brass wedge above a slit 0.7–0.8 mm wide. The wind escaped from the slit at velocities up to about 50 m/sec. The higher pitched tones were not studied, but only those running up to about 1900~/sec. Tones of the first type are less simple than has usually been indicated, and they are described. Tones of the second type become practically simple as they fall toward inaudibility. A number of equations are tested to see which expresses best the relation between frequency N, slit-edge distance h, and the velocity U with which the wind escapes from the slit. It is concluded that the most satisfactory equation is $Nh^s=jU$, where s has, respectively, the values 1.00, 1.14, 1.22, 1.43, and j the values 3.9, 11.8, 24.0, 6.8, for stage I, stage II, stage III, and the second type of edge tones. In this equation h is in mm, and U in cm/sec. Various edge tone phenomena are given qualitative explanation on the basis of the pressure caused alternately on the two sides of the wedge by the injected air, together with the Bernoulli effect on the transverse velocity in the constriction between slit and edge. The velocity of the wind from the windway of one c_2 organ pipe is measured, and found to be about 26 m/sec.

INTRODUCTION

WHEN wind from a slit strikes an opposing edge it may give rise to what is known as an *edge tone*. It has long been recognized that in a flue organ pipe such tones are produced by the wind from the windway striking the upper lip, and that the body of the pipe modifies both the pitch and the quality of the edge tone. Various investigators have examined the edge tones obtained when no organ pipe body is present. In experimental work the edge is often that of a wedge which may be set at different distances from a slit through which the blowing wind issues. There is a minimum slit-edge distance for the production of sound, and the pitch of the sound depends on the width of the slit, the distance from slit to edge, and the air pressure below the slit. With a given slit width an increase in slit-

edge distance, or a decrease in wind pressure, is usually accompanied by a fall in pitch.

One of the early studies was made by Hensen,[1] who reported that an increase in slit-edge distance is not only accompanied by a drop in pitch, but also by a succession of changes in quality, the qualities ranging from soft flute tones or tones accompanied by an octave or twelfth, to the sudden setting in of tones that are distinctly rough. He mentions one case in which the number of definite changes in quality as the slit-edge distance increased was no less than six.

A few years later Wachsmuth[2] found that a gradual movement of the wedge away from the slit may give rise to sudden upward jumps in pitch. He found two such jumps—one of about an octave, and another that was nearer to a fifth. On reversing the motion of the wedge the jumps were also reversed, but not at the same positions of the wedge. There was a lag before the jump occurred, and between the positions for the jump upward with increasing distance and the jump downward with decreasing distance there was an unstable region in which either the higher or the lower tone could be obtained. These jumps in pitch have since been found by various experimenters, and Richardson[3] states that under favorable circumstances half a dozen of them may be obtained.

Benton[4] reported that by taking special precautions to cause the air to approach the slit with streamline motion, and to remove other sources of complication and error, he "also removed the most interesting characteristic of the edge tones studied by Wachsmuth, namely, the succession of breaks in the tone as the distance of the edge from the slit increases." Another very careful study was carried out by Brown,[5] who found that even with great care in the construction and operation of his apparatus he still obtained the jumps in pitch. He distinguished four "stages," separated by the jumps in pitch.

Wachsmuth[2] introduced ether vapor into the blowing wind, and so was able to obtain photographs showing the motion of the air as it streamed past the wedge. These photographs showed that the stream passes alternately to the two sides of the wedge, that it breaks into vortices as it does so, and that the frequency with which the vortices pass a chosen point on one side of the wedge is approximately equal to the frequency of the tone that is heard. Other experimenters have since verified these conclusions, very clear pictures of the vortices have been obtained by Brown,[5] and a considerable amount of study[6] has been devoted to the theory of the tones. In the theory a close relation is usually assumed between the formation of the vortices and the production of the sound.

The present paper distinguishes two types of edge tones. In the first type, at the lower wind pressures, the vortices may be important, and jumps in pitch occur. In the second type, at higher wind pressures, the velocity of the wind is so great that the motion is probably turbulent, and no jumps in pitch occur. Equations to represent the relation between frequency of tone and distance from slit to edge are examined empirically, and for the second type of edge tone some evidence is given for what Richardson[7] has called the "escapement theory" of edge tones.

APPARATUS AND METHOD

The edge used in most of the present work was made on a plate of 4.75-mm sheet brass 10.0 cm $\times$11.7 cm, by grinding one of the 11.7-cm edges to form a wedge of approximately 25°. The plate was mounted on the cross feed for a lathe, so that its level and its sidewise position could be read in thousandths of an inch.

Below the wedge was a wooden box with inner height 13 cm, and inner horizontal section 7.7 cm $\times$7.7 cm. The top of the box was closed by two wooden cheeks about 12 mm thick, between which the sheet of wind blew upward against the wedge. In order to vary the width of the slit one of the cheeks was made adjustable, and could be held in position by two wing nuts. The width of the slit could not be depended upon to remain constant from day to day, probably because of

[1] Victor Hensen, Ann. d. Physik **2**, 719 (1900).
[2] Richard Wachsmuth, Ann. d. Physik **14**, 469 (1904).
[3] E. G. Richardson, *Sound* (Edward Arnold, 1935), second edition, p. 171.
[4] W. E. Benton, Proc. Phys. Soc. **38**, 109 (1925–26).
[5] G. Burniston Brown, Proc. Phys. Soc. **49**, 493, 508 (1937).
[6] For a bibliography of the subject see the end of the second paper cited in footnote 5.
[7] E. G. Richardson, *Reports on Progress in Physics* **5**, 134 (1938).

changes in humidity. In a considerable part of the work the width was measured by a Starrett thickness gauge in which the smallest step was 0.0015 in.

The wind was taken from an ancient blower, and came about 60 ft. through a 4-in. conduit. It was usually possible to detect a faint hum at about 250~ /sec. that probably came from the blower. Slight fluctuations in the blowing pressure were minimized by passing the wind through an 85-liter tank. From this tank the wind passed to a wooden box about 15 cm×16 cm×31 cm, in the top of which were a thermometer and a connection to a water manometer. From this box the wind passed to the box under the wedge. For a few days the Northampton Gas Light Company kindly lent me a gas meter, by which it was possible to find, for various pressures and slit widths, the velocity at which the wind issued from the slit.

Frequencies were determined by comparison with a set of twelve tuning forks with variable loads, running from 112 to 1880~ /sec. Most of the frequencies studied were restricted to these limits. The edge tones were continually fluctuating slightly in pitch, so that the beats between them and the forks were not steady. Moreover, the wind pressure sometimes drifted somewhat during the course of a run, so that the method adopted in a considerable part of the work was to take a set of frequencies with the slit-edge distance increasing, followed by a set with the distance decreasing. At low pressures both sets of readings were made without turning the valve that controlled the wind, and were simply averaged. At higher pressures the valve was turned slightly between the two sets, and interpolation gave frequencies at a chosen intermediate pressure. Many of the earlier runs contained readings at some twenty or thirty positions. In much of the work that is now reported readings were taken at ten positions spaced approximately equally throughout the region to be examined.

A set of Helmholtz resonators aided in picking out faint tones up to about 1500~ /sec.

The temperature was usually between 20°C and 25°C, and during any one run it seldom changed as much as one degree. No corrections for temperature have been made.

WHAT IS HEARD

With the apparatus that I have been using, the phenomena are not as simple as the published descriptions suggest. In describing what I hear I am making use of Brown's term "stage," and I am indicating the distance from slit to edge by the symbol h. The series of events as h increases runs somewhat as follows for a slit width of from 0.7 to 0.8 mm, and pressures of some one or two centimeters of water (velocities of efflux about 900 to 1300 cm/sec.).

With h sufficiently small there is no tone. At the beginning of stage I a clear tone appears suddenly. With increasing h the pitch of this tone falls, and it may be accompanied by at least one or two faint harmonic overtones. The drop of pitch of the principal tone in stage I is about 1.2 octave.

With the advent of stage II the sound becomes suddenly very rough. There are now usually three tones, with frequencies which are not harmonic, but have ratios of approximately 1.0 : 1.8 : 2.8. In spite of the roughness of the sound it is surprising to find this inharmonic relationship in a sound which may continue for some time without much evident fluctuation. As already mentioned, there is an unstable region in which we may have either stage I or stage II for the same setting of h. This makes it possible to compare the frequencies of the two stages for the same h. The lowest of the three tones in stage II is not a continuation of the principal tone in stage I, but has a frequency about 0.85 as great.[8] With increasing h all the tones in stage II fall in pitch, and the roughness becomes less. The middle tone rapidly decreases in loudness, and may soon become inaudible. The lowest tone also decreases in loudness, and it too may become inaudible. The highest of the three is the principal tone in this stage, and its drop in pitch as h increases may be nearly 0.8 octave.

The advent of stage III is also marked by a sudden roughening of the sound, and again there are usually three tones. As in the preceding transition, none of the new tones is a continuation of any tone from stage II. In stage II only one of the three new tones was lower in pitch than the

[8] Brown (my footnote 5) calls attention to this fact, but says that his "results indicate that the frequencies in stage I, when accompanied by other stages, are about 7 percent lower than" his calculations would indicate.

principal tone of stage I. In stage III two of them are lower, the middle one having a frequency about 0.95 that of the principal tone in stage II. The three tones in stage III have frequencies that are approximately in the ratio 1.0 : 3.2 : 5.2. Some faint higher tones may also be present, and a faint tone which is probably the third harmonic of the lowest tone can also at times be detected, so that the frequency ratios become 1.0 : 3.0; 3.2 : 5.2···. The tones 3.0 and 3.2 are both of

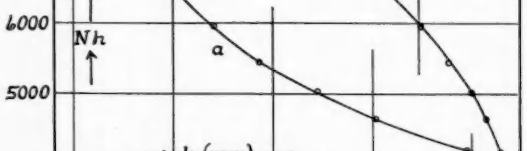


FIG. 1. Nh as functions of h (curve a) and N (curve b). Slit width about 0.8 mm. Pressure 5.90 cm of water. Velocity of wind at slit about 2500 cm/sec.

them faint, and both become inaudible before the end of the stage. 5.2 continues as the principal tone of this stage. As h increases all the tones fall in pitch, and the range in pitch of the principal tone in stage III is in the neighborhood of half an octave.

The advent of stage IV is also marked by some roughness, which, however, soon gives way, as in the preceding stages, to a rather clear tone, which falls in pitch and strength as h increases.

When the pressure is raised to more than 10 cm of water the phenomena are entirely different. There is still a minimum value of h at which the tone begins, but its advent is less sudden—it comes in gently, and grows in loudness rather rapidly. For small values of h the lowest tone may be accompanied by a number of higher ones which are sometimes very irregular and warble back and forth in an erratic manner, so that the whole effect is very unpleasantly shrill and strident. I no longer detect any jumps in pitch, but an increase in h is accompanied by a continuous drop in pitch that may extend over several octaves. The higher components in the sound decrease in loudness more rapidly than the principal tone, until the latter sounds like a simple tone which continues to fall in pitch and strength until it finally dies away.

There seem, then, to be *two different types* of edge tones. One type is that at the lower wind velocities, and the other that at the higher velocities. In the first type there are several "stages," between which occur the characteristic jumps in pitch. In the second type no jumps in pitch occur, but a steady increase in the slit-edge distance is accompanied by a continuous fall in pitch.

At intermediate pressures, say at some 5–7 cm of water (wind velocities about 2200–2800 cm/sec.), the two types of tone seem to be superposed. When h is small the first type of tone is produced, for h somewhat larger both types are present, and as h continues to grow larger the first type fades out and leaves only the second.

RELATION BETWEEN FREQUENCY AND SLIT-EDGE DISTANCE

A considerable part of the work that has heretofore been done on edge tones has seemed to be in satisfactory agreement with the assumption that in any one stage the product of the frequency N and the slit-edge distance h is nearly constant. Carrière[9] has published one set of ten observations which is not in agreement with this assumption. An increase of h which caused the pitch to drop about 1.5 octaves was accompanied by a decrease in Nh of more than 22 percent. Carrière represented his result by writing $Nh^{1.5}=\text{const.}$

Brown[5] found that his own experimental results are well represented by the equation

$$N=0.466j(U-40)(1/h-0.07), \qquad (1)$$

where $j=1$, 2.3, 3.8, 5.4 for stages I, II, III, IV, respectively. U stands for the velocity of the wind (in cm/sec.) as it leaves the slit, and h is measured in centimeters. If in this equation we write

$$C=4.66j(U-40), \qquad (2)$$

C will be constant for given apparatus with constant slit width, constant wind pressure, and any one stage. If, further, h is measured in millime-

[9] Z. Carrière, J. de phys. et rad. **6**, 52 (1925).

ters, then (1) may be written in the form

$$(N+x)h=C, \qquad (3)$$

where x stands for $0.007C$. Brown says that his equation, representing results obtained with a 1-mm slit, a wedge angle of 20°, and air at 20°C, gives frequencies correctly within 6 percent for the range $N=20$–$5000\sim$/sec., and for wind velocities running from 120 to 2000 cm/sec. The work that I am reporting has a considerably smaller range of frequencies, but involves wind velocities that probably run up to at least 2.5 times the above maximum, i.e., to wind velocities in the neighborhood of 100 miles/hour—corresponding to a pressure of about 30 cm of water.

I have examined a number of equations to see which fits best the experimental results that I have obtained with a slit width of 0.7–0.8 mm. The equations tested are: (*a*) $Nh=C$, (*b*) $Nh^s=C$, (*c*) $(N+x)h=C$, (*d*) $N(h+y)=C$, (*e*) $(N+x)\times(h+y)=C$, (*f*) $(N+x)h^s=C$, (*g*) $N(h+y)^s=C$, and a couple of more complicated equations. C, s, x, and y are constants. s, x, and y are chosen for each set of observations,[10] and when they have been chosen a value of C is found from each pair of experimental values of N and h. The average deviation of these values of C from their mean is taken as indicating the satisfactoriness of the equation.

Before turning to the results of these tests a few conclusions may be drawn more simply. In stage I, for the width of slit that I have been using, the values of Nh are nearly the same at the beginning of the stage and at the end of it, but in the middle are some 2.5 percent–3 percent larger. In all other cases that I have examined, with this width of slit, the values of Nh decrease with increasing h. For stage I it follows that no equation of the form (*c*) or (*d*) can represent the facts accurately. Thus where the Nh in (*c*) increases with increasing h it is necessary for x to be negative, whereas where Nh decreases with increasing h, x must be positive. Since x is a single constant it cannot be part of the time positive and part of the time negative. Similar reasoning applies to (*d*). In fact, because of the way in which Nh changes in stage I it proved impracticable to find the x or y for (*c*) or (*d*) by the method outlined in footnote 10, and these two equations as they stand were not tested for stage I.

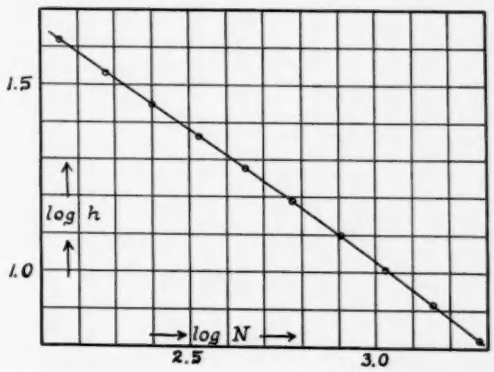


FIG. 2. Plot of log N against log h. Slit width about 0.8 mm. Pressure 19.00 cm. Velocity of wind about 4500 cm/sec.

In stages II and III the drop of Nh as h increases is not great. The value of Nh at the beginning of one of these stages is some 7 percent larger than at the end of the stage. In the second type of edge tones Nh for h small is more than twice as large as it is after the pitch has dropped four octaves. Evidently Eq. (*a*) is not satisfactory for the second type of edge tones.

If Nh is plotted against either h or N, the observations for stages II and III give fair approximations to straight lines. A straight line on the Nh–h plot would mean that the observations satisfied an equation of the form (*c*), and a straight line on the Nh–N plot would mean that they satisfied an equation of the form (*d*). Thus either (*c*) or (*d*) may be expected to be fairly satisfactory for stages II and III. My stage IV observations are restricted to a single run, they are not very accurate, and the points on the plot

[10] No least square determination of the constants seemed worth while. In (*b*), (*c*), and (*d*) two equations were obtained by putting into the equation to be tested a pair of experimental values of N and h. From the two equations C was eliminated, and the resulting equation was solved for the desired constant. In most cases N had been found for ten values of h, and in these cases the value used for the desired constant was the average of the five obtained by using the N and h from the first and sixth observations, from the second and seventh, etc. In (*e*), (*f*), and (*g*) two constants were to be found in addition to C. This required three equations. The observations to be used for the three were selected by inspecting a curve that coordinated log N and log h. For (*e*) C was eliminated, and the solution for x and y was perfectly straightforward. For (*f*) and (*g*) C and s were eliminated, x or y found by a process of successive approximation, and s determined from one of the equations which had already been reached.

scatter considerably, but they fit a straight line as well as any other curve.

For the second type of edge tones neither the Nh–h plot nor the Nh–N plot is even approximately straight. Figure 1 is typical. It is clear that for edge tones of the second type no equation of the form (*c*) or (*d*) can fit the facts.

A plot of log N against log h is nearly always approximately straight. I have made thirty such plots. All but one[11] are nearly straight, at least half bend slightly, with the concavity on the side of small N and small h, and one bends slightly in the opposite directon. Figure 2 gives a typical curve, showing about the usual amount of slight bending. Since these curves are nearly straight, it follows that if s is properly chosen an equation of form (*b*) will fit most of the observations rather well.

Pass next to the tests by means of the average deviations. For the first type of edge tones, where the range of pitch is never much greater than an octave, all of the equations tested are fairly satisfactory. Even with (*a*) the largest average deviations amount to about 2 percent. With (*b*) and stage I the average deviations are about 1 percent, and with the same equation and the other stages they run from 0.1 percent to 0.3 percent. With (*c*) and (*d*) most of the average deviations are a few tenths of a percent. The Eqs. (*e*), (*f*), and (*g*), each of which contains two constants in addition to C, give somewhat closer fits, with average deviations in most cases less than 0.2 percent.

TABLE I. Velocity of wind at slit (cm/sec.).

Pressure (cm)	Experimental	By Brown's equation	By modified equation
0.53	610	585	612
0.87	815	737	796
1.44	1100	983	1052

For the first type of edge tones Brown's equation gives average deviations of about 1 percent. From his equation it is possible to calculate the velocity of the wind as it leaves the slit. These velocities are shown in Table I, and may probably be regarded as in satisfactory agreement with the rather rough experimental values.

[11] This was a short run in preliminary work. Slit width 1.40 mm. Pressure 28.9 cm of water. Range of frequencies about 2.4 octaves.

I have tried to modify Brown's equation by employing a different constant in place of his 0.07. My observations are fitted best by choosing a constant about twice as large. Using 0.15 instead of 0.07 the results for stage I are not as good as with the original equation, the average deviations now being about 1.5 percent to 2 percent, but for stages II and III the average deviations are smaller, averaging about 0.5 percent. The values for the velocity of the wind calculated from the modified equation are somewhat improved, if the observed values are to be trusted to this extent. These values are shown in Table I.

For the second type of edge tones, where the ranges of pitch examined lie between 3.4 and 3.9 octaves, some of the equations are definitely not as good as others. The poorest fit is with (*a*), where the average deviations are about 20 percent. (*d*) comes next, with average deviations of about 12 percent. (*c*) gives average deviations in the neighborhood of 4 percent. (*b*), (*e*), (*f*), and (*g*) are better. The smallest average deviations are obtained with (*g*), where they do not exceed 0.6 percent. With (*f*) they are more than twice as large as with (*g*), and with (*e*) more than twice as large as with (*f*). With (*b*) they lie between those for (*e*) and (*f*). Brown's equation gives average deviations of about 15 percent, and the modified Brown's equation of 6 percent to 10 percent.

Each constant has been chosen to fit a single set of observations.[12] It is desirable that the constant finally adopted should fit all observations. For (*e*), (*f*), and (*g*) the values of the constants for the different sets of observations vary considerably more than they do for (*b*). Moreover, for (*g*) the variation is less than for (*e*) or (*f*). An average value for the s in (*b*), and averages for the s and y in (*g*), have therefore been found, and the results of calculations of four sets of observations, making use of these averages, are shown in Table II. The somewhat better fit with (*g*) in three of the cases, and its poorer fit in one of them, do not seem to warrant choosing this

[12] The choice of one of the two constants in (*e*), (*f*), or (*g*) is not at all critical, provided that the other constant is chosen to agree with it. Two illustrations may be given. In one case (pressure 0.90 cm, stage II) the choice $x=125$, $y=-0.02$ in (*e*) gave an average deviation of 0.15 percent; $x=314$, $y=+1.68$ gave an average deviation of 0.19 percent. For the same case the choice of $x=123$, $s=1.004$ in (*f*) gave 0.17 percent; $x=648$, $s=0.646$ gave 0.14 percent.

slightly more complicated equation. As an empirical equation to express the relation between N and h in the second type of edge tones, and under the circumstances of the present study, $Nh^{1.43}=C$ gives results in which the average deviations from the mean obtained for C do not exceed 2 percent.

For the first type of edge tones I find that if the s in (b) is chosen as 1.00 for stage I, 1.14 for stage II, and 1.22 for stage III, the average deviations run from 0.3 percent to 0.9 percent.

The C in (b) depends on the velocity of the wind. For each of the stages I, II, III, and for the second type of edge tones, it appears to be approximately proportional to that velocity. As already stated, my values for the velocity of the wind are not very accurate. However, for the circumstances under which I have worked, and with a slit width of about 0.7–0.8 mm, the most satisfactory expression that I have found for the frequency of edge tones is

$$Nh^s=jU, \tag{4}$$

in which s has, respectively, the values 1.00, 1.14, 1.22, 1.43, and j the values 3.9, 11.8, 24.0, 6.8 for stages I, II, III, and for the second type of edge tones. In this equation N stands for the frequency of the tone in $\sim$/sec., h for the distance from slit to edge in mm, and U for the velocity of the wind as it leaves the slit, in cm/sec. For stage I (4) gives nearly the more common approximation $Nh=5U$.

EXPLANATION OF EDGE TONES

Most of the following discussion has to do with edge tones of the second type. In this type the velocity of the wind is so great that the air sheet is probably turbulent when it leaves the slit, or becomes turbulent within a very short distance. Under these circumstances there can hardly be anything at all resembling a Kármán street of vortices, or indeed discrete vortices that are distributed in any regular manner. In the following paragraphs the sound is regarded as produced by the compressions that arise from the injection of masses of air, first on one side of the wedge and then on the other. This point of view is not new, but, so far as I know, I am carrying it further than any one has before.

The wind that passes to either side of the wedge introduces a mass of air which sets up a compression that travels outward in all directions with the velocity of sound. If more air is introduced on one side of the wedge than on the other the difference between the compressions on the two sides gives rise to a sidewise motion of the air between the slit and the edge. The particle velocity in a compression increases as the compression approaches the constriction between the slit and the edge, and may well become great enough to carry the air sheet with it. Thus the blowing of the wind to either side of the wedge produces a compression that tends to swing the air sheet to the other side. The pressure on either side of the wedge will continue to build up after the air sheet has reached its greatest displacement. This is partly because every elementary mass of air tends to move on in the direction of its momentary resultant velocity, and partly because some time is required, short though it may be, for the pressure to spread backward to the region between the slit and the edge. It follows that the force which urges the air sheet toward the other side of the wedge will have a component in phase with the velocity, and maintenance of the vibratory motion is possible.

If the air pressure below the slit is increased the air sheet will deliver a larger mass of air in the same time, the difference between the pressures at the sides of the wedge will increase, the rapidity of the transverse flow between slit and edge will increase, and the pitch will rise. It is well known that an increase in blowing pressure does produce a rise in pitch.

TABLE II. Comparison of results obtained by using $Nh^{1.43}=C_1$ and $N(h+1.44)^{1.57}=C_2$.

Pressure (cm)	Av. dev. of C_1(%)	Av. dev. of C_2(%)
5.90	1.59	3.02
10.30	1.89	0.73
19.00	1.66	0.89
28.80	1.95	0.64

An increase in the width of the slit, with the blowing pressure unchanged, also provides a more rapid delivery of air, and so would be expected to lead to a higher pitch. Experiment shows that this is the case.[9]

If the distance from the slit to the edge is increased, a compression which travels toward

TABLE III. Fractions of a period in which a mass of air would rise from slit to edge if it did not slow down.

Tone	Fraction of period	
	h small	h large
Stage I	0.38	0.38
Stage II	0.91	0.85
Stage III	1.38	1.30
2d Type	0.30	0.15

the constriction between the slit and the edge will have a larger opening through which to pass, the velocity of the transverse flow through the opening will decrease, and the frequency of vibration of the air sheet will drop. It is well known that increase of slit-edge distance does lower the observed pitch.

It might seem at first that doubling the slit-edge distance h would halve the velocity of transverse flow, and would therefore halve the frequency N, so that Nh would be independent of h. But the velocity with which a compression travels is not changed, and as N goes down, and more time is thus given for the spreading of compressions, a decrease is to be expected in the pressure gradient, and this would further lower N. So it would seem that the fractional change in N would be greater than that in h. This would make Nh a decreasing function of h, as it is except in stage I. The relation between N and h depends on additional factors, and the precise relationship is difficult to foresee.

The lowering of pitch with increasing h is accompanied by an increase in wave-length. The linear dimensions of the plate on which the wedge has been formed are therefore smaller and smaller fractions of the wave-length, the plate serves as a less and less effective baffle, and an increase in the distance from slit to edge may be expected to be accompanied by a falling off in the intensity of the sound. As a matter of fact, the sound does grow fainter as the slit-edge distance increases. This is especially noticeable with the second type of edge tones. Moreover, with this type the lowest pitch that is audible appears to be practically independent of the blowing pressure. At the higher pressures the lower limit of audibility occurs at larger slit-edge distances. Perhaps the increase of intensity by the higher pressure is just about compensated by the lowering of intensity brought about by greater distance. In a number of tests with plates of different sizes I have found the sound audible until the smaller dimension of the plate was in the neighborhood of 0.02λ.

The slit must be of finite width. If the wedge is lowered until its edge is at the same level as the top of the slit there will be little opportunity for the air sheet to swing back and forth past it. The air sheet can hardly begin to vibrate until the wedge has been withdrawn to a sufficient distance from the slit. If a vibration did occur it would be at a high frequency, and the higher the frequency the more important the inertia of the air becomes. A minimum slit-edge distance before sound can be produced seems reasonable.

The wider the slit the greater this minimum distance might be expected to be. A rather rough test showed that from a slit width of 0.7 mm to one of about 2 mm this expectation seemed to be correct, at least up to pressures of about 5 cm of water.

If the wedge is almost far enough from the slit for a tone to be produced, it seems likely that an increase in the blowing pressure might produce a sufficient difference of pressure on the sides of the wedge for a tone to begin. With the first type of edge tones experiment shows[13] that the minimum slit-edge distance for tone production does definitely decrease when the blowing pressure rises. With the second type the tone begins much less abruptly, but with this type the effect seems to be reversed.

If the time occupied by a given mass of air in rising from slit to edge were several cycles of the tone produced, it might be expected that a gradual increase in the slit-edge distance would give rise to phenomena which would repeat. From values of the slit-edge distance and the corresponding frequency of the edge tone, together with the velocity of the air sheet at the slit, it is easy to calculate how many cycles, or fractions of a cycle, would be occupied by such a mass if its upward velocity did not decrease with distance. Using the rough values that I have for the velocities I find the average values given in Table III. Since the sheet of air does slow down,[14] it would seem that in stage I a given mass of air

[13] This was shown by Benton (my footnote 4), and I have verified his result.

[14] E. G. Richardson, Proc. Phys. Soc. **43**, 394 (1931).

rises to the edge in about half a period, in stage II in about one period, and in stage III in about a period and a half. Similar values can be calculated from Fig. 3 in Brown's paper.[5]

If the air were without inertia, and if no vortex motion were involved, the shapes assumed by the air sheet would probably be similar to those sketched theoretically by Mach[15] for a narrow flame subjected to transverse waves of sound. Under these circumstances it is difficult to see how a tone could be produced when the air rose from slit to edge in an integral number of periods. For at the end of an integral number of periods the transverse motion would bring the air back to the mid-position directly above the slit, instead of deflecting it to one side. However, as already mentioned, the inertia of the air prevents it from taking up the transverse motion immediately. If, as a rough approximation, we assume that the air flows directly upward for a quarter of a period, and then takes on the transverse motion, the numbers just given would suggest that when the level of the edge is reached the transverse motion in stage I has been going on for about a quarter of a period, in stage II for about three quarters of a period, and in stage III for about five quarters of a period. These times would be of the right order to give a maximum displacement at the level of the edge.

In the second type of edge tones the fraction of a period occupied by the air in passing up to the level of the edge decreases somewhat as the wind velocity increases. It is probably always less than half a period.

I have found the velocity of the wind as it comes from the windway of one organ pipe. This is a large scale wooden flute, with interior cross section 8.30 cm×9.95 cm, speaking the *c* below middle *c*, and voiced on four inches of water. When the air comes from the windway it has a velocity of about 26 m/sec., i.e., nearly 60 miles/hour, and a given mass of air crosses the mouth in something like a fifth of a period.

[15] Ernst Mach, *Optisch-Akustische Versuche* (Calvé' 1873), p. 52.

Comparison Between a Haskell Organ Pipe and a Simple Open Pipe

R. C. BINDER AND A. S. HALL
School of Mechanical Engineering, Purdue University, Lafayette, Indiana
(Received August 6, 1942)

An analysis with friction shows that the mobility for a Haskell organ pipe is not exactly equal to that for a simple open pipe. The inclusion of friction probably explains the observation that a Haskell pipe and a simple open pipe blown in exactly the same way show substantial differences in harmonic structure.

THE Haskell organ pipe has characteristics of an open pipe while being more compact. Jones[1] presented some analytical work, neglecting friction, for the Haskell pipe, together with some experimental data. Trimmer[2] stated that a Haskell pipe and a simple open pipe blown in exactly the same way show substantial differences in harmonic structure. The following presents an analysis of the Haskell organ pipe with friction; this indicates that the mobility of a Haskell pipe is not exactly equal to that of a simple open pipe.

CALCULATION OF MOBILITY

Following Firestone,[3] the acoustic mobility (ease of motion) is defined as the complex ratio of the volume velocity amplitude to the sound pressure amplitude. For the simple open pipe shown in Fig. 1(a), the specific acoustic mobility Z is

$$Z=(1/\rho c)\coth(\alpha+i\omega/c)l, \tag{1}$$

where ρ is density, c is velocity of sound, α is an attentuation factor, ω is circular frequency, and l is length.[4] Lengths in this discussion are those after end corrections have been applied.

The Haskell organ pipe is represented in Fig. 1(b). Let S represent cross-sectional area. The case will be taken in which $S=2S_1=2S_2$ and $b=e$. These relations are very nearly satisfied in the Haskell pipes. At the junction A the pressure is the same in each area, and the volume velocity from the pipe of area S equals the sum of the volume velocities into pipes of area S_1 and S_2.

Using the basic equation given by Crandall[4]

$$Z_H=\frac{1}{\rho c}\left[\frac{(1+\rho cZ_a)-\exp\left[-2(\alpha+i\omega/c)a\right](1-\rho cZ_a)}{(1+\rho cZ_a)+\exp\left[-2(\alpha+i\omega/c)a\right](1-\rho cZ_a)}\right], \tag{2}$$

where α is the attenuation factor in the tube of length a, and Z_a is the mobility at the end of length a due to the two pipes in the length b. The case is taken in which the attenuation factor α_2 in the tube of area S_2 equals the attenuation factor α_1 in the tube of area S_1. Then

$$Z_a=(1/\rho c)\coth 2(\alpha_1+i\omega/c)b. \tag{3}$$

Inserting Eq. (3) in Eq. (2) gives, as a final result,

$$Z_H=(1/\rho c)\coth\left[(\alpha+i\omega/c)a+2(\alpha_1+i\omega/c)b\right]. \tag{4}$$

The important feature is a comparison of Eqs. (1) and (4).

If the fluid is frictionless, then $\alpha=0$ and $\alpha_1=0$. For this case

$$Z=(1/\rho c)\coth(i\omega/c)l,$$
$$Z_H=(1/\rho c)\coth(i\omega/c)(a+2b) \tag{5}$$

and the Haskell organ pipe has the same mobility and the same resonant frequencies as a simple open pipe when $l=a+2b$. For resonant frequencies (i.e., when the mobility is infinite) $\sin(\omega/c)(a+2b)=0$.

ROLE OF FRICTION

If the friction is the same in each separate region, if $\alpha=\alpha_1$, then the Haskell organ pipe has

[1] A. T. Jones, "Theory of the Haskell organ pipe," J. Acous. Soc. Am. **8**, 196 (1937).
[2] J. D. Trimmer, "Resonant frequencies of certain pipe combinations," J. Acous. Soc. Am. **11**, 129 (1939).
[3] F. A. Firestone, "The mobility method of computing the vibration of linear mechanical and acoustical systems: mechanical-electrical analogies," J. App. Phys. **9**, 373 (1938).
[4] I. B. Crandall, *Theory of Vibrating Systems and Sound* (D. Van Nostrand, 1926), p. 100.

the same mobility and the same resonant frequencies as a simple open pipe when $l=a+2b$. The mobility has a maximum in absolute value for the resonant frequencies. The resonant frequencies are the same as those for the case of no friction.

A real question exists as to the relative magnitudes of α and α_1. Since the areas are different, it seems reasonable to expect that α will be different from α_1 (or α_2). The Helmholtz-Kirchhoff theory, in the absence of more definite information, might be used to estimate the relative magnitudes of the attenuation factors. This theory states that

$$\alpha=(2/dc)[(\omega/2)(\nu+\sigma)]^{\frac{1}{2}}, \qquad (6)$$

where d is the tube diameter, ν is the kinematic viscosity, and σ is the thermal diffusivity of the fluid. Equation (6) shows that $\alpha_1=\sqrt{2}\alpha$ for the Haskell organ pipe.

The two expressions $(\alpha+i\omega/c)l$ and $(\alpha+i\omega/c)a+2(\alpha_1+i\omega/c)b$ are exactly equal only when the real part of one equals the real part of the other

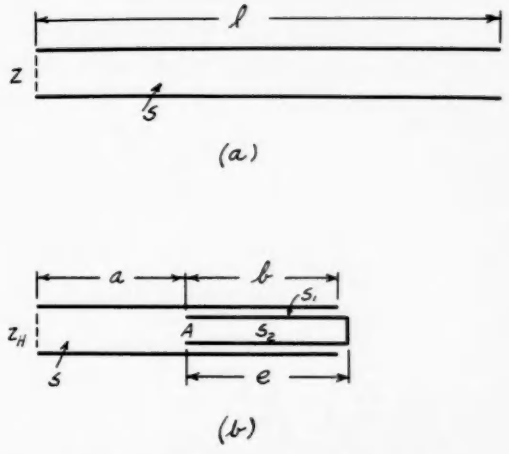


FIG. 1. (a) Simple open pipe. (b) Representation of Haskell pipe.

and the imaginary part of one equals the imaginary part of the other. Both of these conditions cannot be satisfied at any one frequency if α does not equal α_1. In this case the Haskell pipe does not have exactly the same mobility as a simple open pipe. The magnitude of α (and α_1) is different at various frequencies. The difference in mobility between a simple open pipe and a Haskell pipe will be different at various frequencies. As an example, Fig. 2 shows a plot

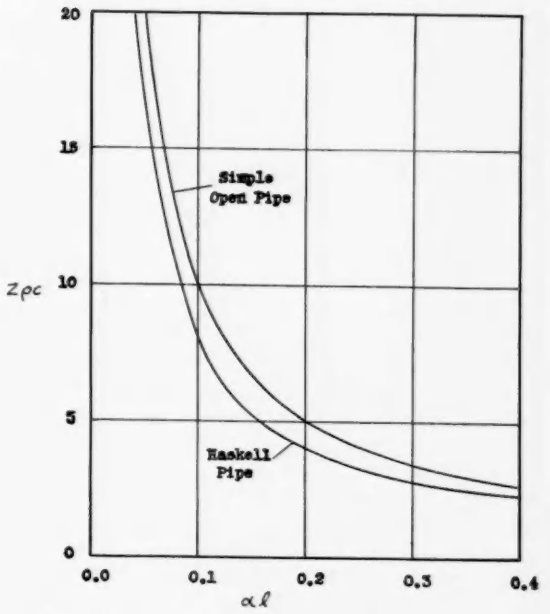


FIG. 2. Mobility of a Haskell pipe and an open pipe *vs.* αl for resonant frequencies. $a=b=l/3$.

of the mobility of each pipe *vs.* αl for resonant frequencies. Figure 2 is for the case in which $a=b=l/3$, and $\alpha_1=\sqrt{2}\alpha$.

If a Haskell pipe and a simple open pipe are blown in the same way, it seems reasonable to expect that different mobilities of the driven elements will result in the source of one performing differently from the source of the other. This frictional effect seems to offer a reasonable explanation of the differences in harmonic structure reported by Trimmer and confirmed by Hunt.[2]

If α_1 is different from α_2, the mobility for a Haskell becomes more complicated than that given by Eq. (4); the result gives a mobility difference greater than that between Z and Z_H. Because of greater surface area alone, it is quite possible that α_1 is greater than α, and that α_1 is greater than α_2. These possibilities cannot be settled at the present time because the mechanism of the attenuation has not been completely established.

In general, Eq. (6) indicates that α is probably small in comparison with ω/c. There are experimental data, as those of Lehmann,[5] however,

[5] K. O. Lehmann, "Die Dampfungsverluste bei starken Schallswingungen in Rohren," Ann. d. Physik **21**, 533 (1934).

which show that the absolute value of the attenuation factor is considerably higher than that given by the Helmholtz-Kirchhoff theory. For a frequency of 50 cycles per sec., and a pipe diameter of 2.64″, measurements by Lehmann show values of α of about 0.0003 per inch for small pressure amplitudes. For larger pressure amplitudes (greater than about 0.4 pound per sq. in.) α increases with amplitude. It should be noted that there are numerous cases in which a very small amount of friction has a noticeable effect on the phenomena involved.

Notes on Acoustic Impedance Measurement

HALE J. SABINE
The Celotex Corporation, Chicago, Illinois
(Received August 16, 1942)

THE recent emphasis on acoustic impedance as a means of describing the sound absorbing properties of acoustical materials has brought about a renewed interest in tube methods of impedance measurement. Preparatory to the construction of an impedance tube by the writer, an examination of the literature[1] revealed an abundance of mathematical analyses pertaining to the various tube methods, but a comparative lack of detailed data covering design, construction, and measuring technique. It was possible to obtain much of this data only by first-hand consultation with other experimenters who had built tubes, and later from experience with our own apparatus. The following notes summarize this information and are offered with the hope that they may be of guidance and time-saving value to future experimenters in this field.

The apparatus just referred to was designed for the purpose of commercial development of acoustical materials, and to this end the following considerations were observed: (a) The absorption coefficient is generally of more immediate interest, and is therefore more frequently determined, than is the impedance of a sample. Impedance data are of value chiefly in interpreting the trend of absorption coefficients with respect to other physical properties of the material. The phase angle of the impedance may also have a bearing on the relation between tube coefficients and room coefficients. (b) Measurements must be made easily and rapidly, particularly those from which absorption coefficients are determined. (c) Measurements should be made on standard 12-inch square samples, thus avoiding the necessity of cutting them to a smaller size. (d) Means should be provided for various types of sample mounting which duplicate as closely as possible the standard types of mounting used in commercial reverberation chamber tests and in actual construction. (e) Extreme accuracy is not required. Ability to repeat absorption coefficients to within 2 points is regarded as satisfactory. (f) The design should avoid complicated or high precision machine work as far as possible.

Items (a) and (b) led to the choice of the tube method identified by having a fixed length of tube, fixed sound source, fixed frequency, and movable pressure detector.[2–5] (See Fig. 1.) Normal incidence sound absorption coefficients, α_n, are measured according to the original analysis of H. O. Taylor,[6] which is given in a number of standard texts on architectural acoustics. By means of the movable microphone, the difference in decibels, L, between the maximum and minimum sound pressure in the standing wave is measured and inserted in the formula,

$$\alpha_n = 1 - \left(\frac{\log_{10}{}^{-1} L/20 - 1}{\log_{10}{}^{-1} L/20 + 1}\right)^2 = 1 - k^2, \quad (1)$$

[1] L. L. Beranek, J. Acous. Soc. Am. **12**, 3 (1940), references 1–15.

[2] P. M. Morse, *Vibration and Sound* (McGraw-Hill, 1936), p. 209.

[3] A. H. Davis, *Modern Acoustics* (G. Bell and Sons, 1934), p. 207.

[4] R. H. Bolt and R. L. Brown, J. Acous. Soc. Am. **12**, 31 (1940).

[5] W. M. Hall, J. Acous. Soc. Am. **11**, 140 (1939).

[6] H. O. Taylor, Phys. Rev. **2**, 270 (1913).

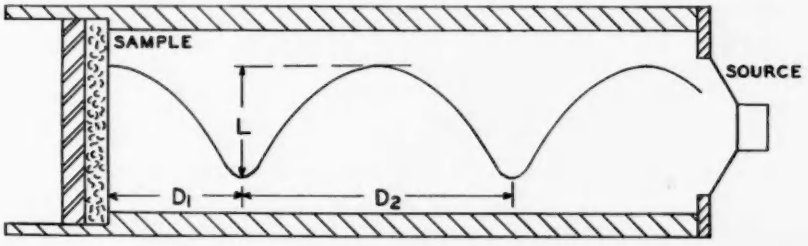


FIG. 1. Standing wave pattern in an impedance measuring tube.

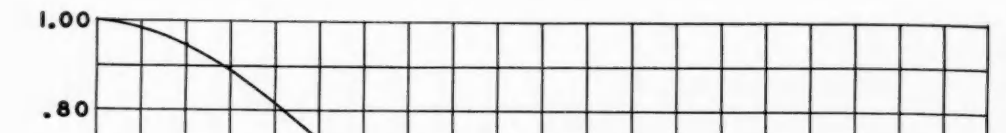


FIG. 2. Curve showing relation of normal incidence absorption coefficient α_n to the difference in decibels L between the maximum and minimum sound pressures.

where k is the pressure reflection coefficient of the sample. A plot of this formula is given in Fig. 2, by means of which absorption coefficients can be immediately determined.

In order to determine the impedance of the sample, it is necessary, in addition to the measurement of L, to find the ratio D_1/D_2, where D_1 is the distance from the surface of the sample to the first pressure minimum, and D_2 is the distance between the first and second minima (equal to one-half wave-length). The resistive and reactive components of the impedance are obtained from these two measurements by the formulae[3*]

$$R/\rho c = \frac{1-k^2}{1+k^2+2k\cos(2\pi D_1/D_2)},$$
$$X/\rho c = \frac{2k\sin(2\pi D_1/D_2)}{1+k^2+2k\cos(2\pi D_1/D_2)}. \qquad (2)$$

Direct reading charts of Eq. (2), drawn with L and D_1/D_2 as contours on the $R/\rho c$, $X/\rho c$ plane, are given in Fig. 3. These will be recognized as plots of the hyperbolic tangent of a complex quantity, such as have been published by Kennelly,[7] Morse,[8] and by Hall,[5] but which for this particular application have been redrawn to finer detail and with altered parameter units. The L contours are very easily plotted, since each contour is a circle having a radius of $2k/(1-k^2)$, and whose center is displaced along the horizontal axis a distance $(1+k^2)/(1-k^2)$. The D_1/D_2 contours must be plotted point by point from Eq. (2).† It will also be noted that the L contours show the relation of the absorption coefficient to the impedance, since each value of L may be replaced by the corresponding value of α_n given by Eq. (1).

The remaining requirements listed above resulted in the tube design shown in Fig. 4. The tube is built of $1\frac{1}{2}''$ slate weighing 22 pounds per square foot. It is 10 feet long and $11\frac{1}{2}$ inches square inside. This length establishes a lower frequency limit, if two pressure minima are measured, of about 85 cycles. The upper frequency limit is determined by the point at which transverse modes of vibration contribute appreciably to the wave motion in the tube, a condition which is evidenced by wide and irregular discrepancies between the values of successive minima. This would be expected to occur at a wave-length equal to twice the tube diameter, in

* The same formulae are given in exponential notation in references 2 and 5.

[7] A. E. Kennelly, *Chart Atlas of Complex Hyperbolic and Circular Functions* (Harvard University Press, 1924).

[8] Reference 2, pp. 341, 342.

† For values of L greater than about 30 db, the D_1/D_2 contours are very nearly circular arcs each having a radius of $\frac{1}{2}\tan(2\pi D_1/2D_2)$ whose center is displaced along the vertical axis a distance equal to the negative of the radius.

this case in the proximity of about 600 cycles, and other investigators[4,9] have observed this effect. However, with this apparatus, interference is not encountered until the frequency approaches the second transverse mode at approximately 1200 cycles. The upper frequency limit for accurate readings is about 800 cycles, although fairly reliable indications can be obtained at 1000 cycles. The absence of interference by the first transverse mode is attributed to the arrangement of the sound source, as shown in the close-up of Fig. 6. A smaller diameter tube would of course make possible a higher frequency limit, but it was thought preferable to be able to make measurements on full size samples.

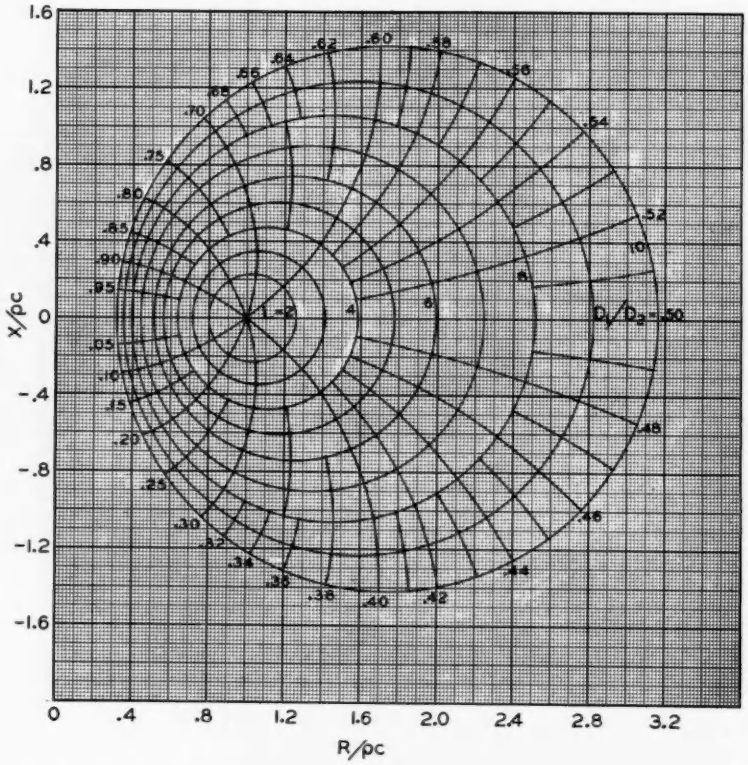
The sample mounting chamber, shown in Fig. 5, was designed with a view to flexibility of mounting conditions together with rapid changing of samples. The inside dimensions are slightly larger than $12\times12''$ in cross section. The walls and removable cover are of $\frac{1}{2}''$ steel plate, and the backer plate is $\frac{3}{4}''$ thick. The backer is fitted with a lead screw by which the sample is held against stops which are flush with the $11\frac{1}{2}''$ cross section of the tube. These stops furnish accurate and positive positioning of the sample; this is important because the face of the sample is the reference point from which the distances D_1 and D_2 are measured. The chamber is deep enough to permit an air space variable up to 12″ behind the sample. The combined effects of leakage around the backer and cover plate and radiation through the chamber walls are responsible for a measured effective normal incidence absorption coefficient, with no sample, of about 0.03. This is considerably smaller than the lowest sample coefficients which are of interest.

As mentioned above, efforts are made to duplicate commercial methods of mounting as closely as possible. A No. 1 mounting (cemented to plaster board) is simulated by inserting between the sample and the backer a layer of plaster board to which are adhered four daubs of acoustical adhesive which have been flattened down to about $\frac{1}{8}''$ thickness and allowed to dry and harden. The purpose of this arrangement is to save time and to avoid spoiling samples by actually cementing them to plaster board. A No. 2 mounting is effected simply by the insertion of standard furring strips between the sample and the backer. In this connection, it may be reported that some types of sample exhibit large variations in absorption with slight changes in the mounting conditions, particularly with variations in the pressure of the backer plate. This tendency appears to be more pronounced in light materials of the board type than in more rigid, dense, and inelastic materials. Further data have not been collected on this point, but it is mentioned here as an important source of possible discrepancies in tube measurements.

The pressure detector is a Brush crystal sound-cell microphone, carried inside the tube on the end of a light metal H-bar, the other end of which projects outside the tube at the source end. This end of the bar is fitted with small rubber wheels which roll on a track, as shown in detail in Fig. 6. A similar pair of wheels at the microphone end travel on a track inside the tube. The sound cell lies in a horizontal position at approximately the center of the tube's cross section. The top surface of the H-bar carries a fine-toothed rack (not shown in Fig. 6) over its entire length. This rack engages a pinion on the crank shaft of the drive mechanism. The latter unit is designed to serve also as a revolution counter, the pointers on the four dials being connected together through a train of 10-to-1 gears. The pointer on the lowest dial is used as a vernier for fine adjustment in locating sharp pressure minima. Thus, the microphone is moved up and down the tube by turning the crank of the drive mechanism, and the distance of a minimum thus located from the surface of the sample is read from the four dials in the same manner as a watt-hour meter. The dial readings do not have to be converted to inches or centimeters, since it is only the ratio of the distances that is needed.

The details just described have several advantages. Placing the microphone inside the tube avoids difficulties which would be encountered with a probe tube and external microphone, such as extremely low sensitivity, noise interference, etc. Provision of a rigid connection between the microphone and its position indicator eliminates errors due to stretching or slack in a wire or string connection. The rubber wheels minimize

[9] Reference 3, p. 213.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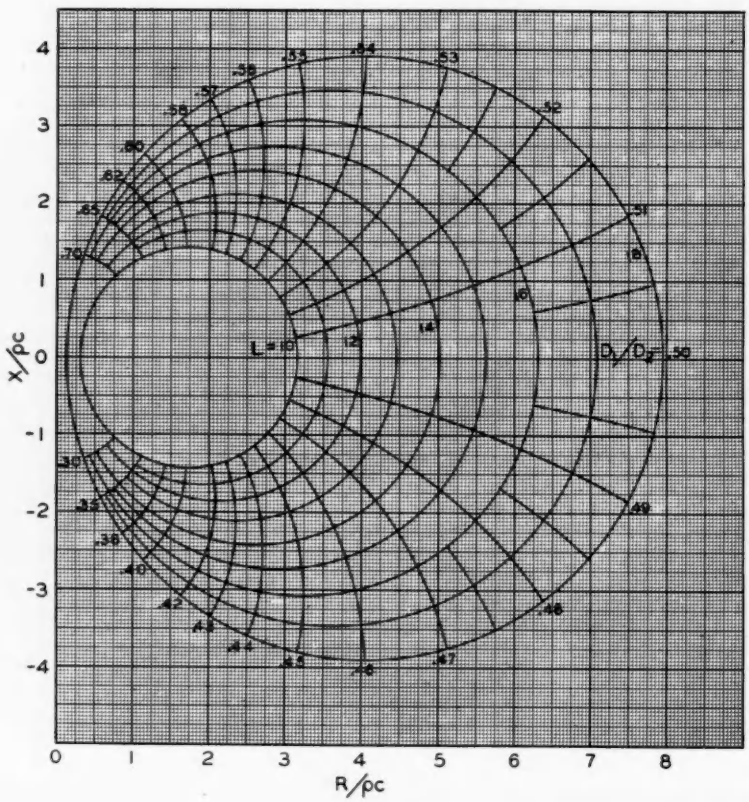
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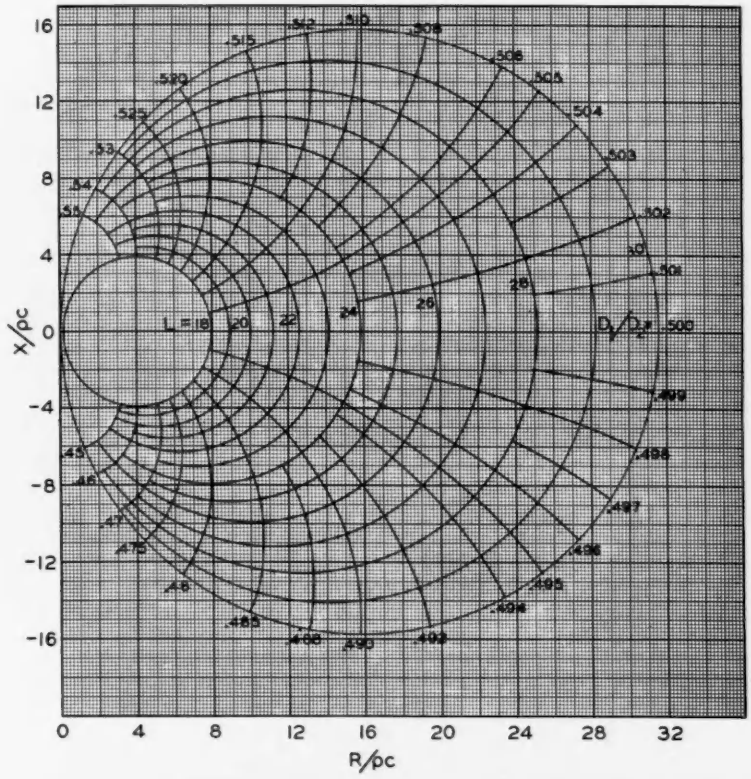

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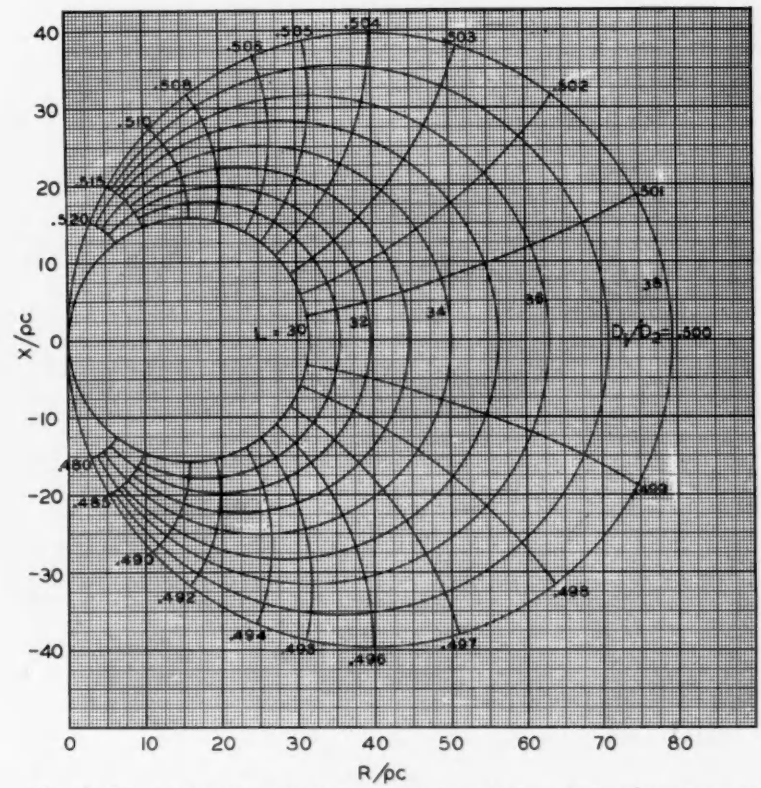


D

FIG. 3. Charts showing relation of acoustic resistance R and reactance X to parameters L and (D_1/D_2).

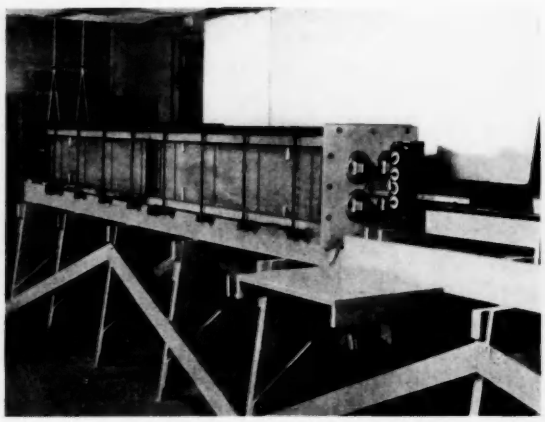


FIG. 4. General view of impedance measuring tube.

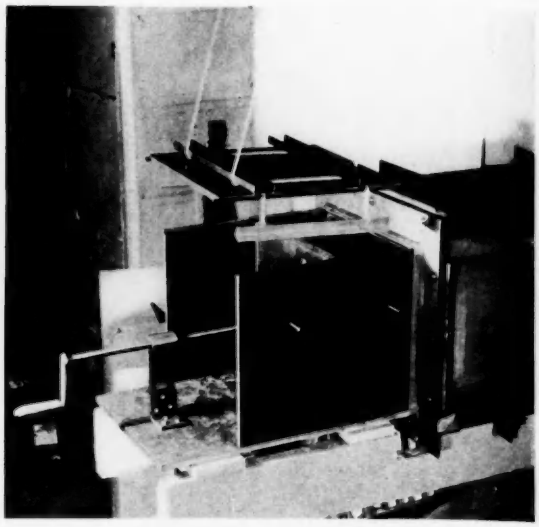


FIG. 5. Details of sample mounting chamber.

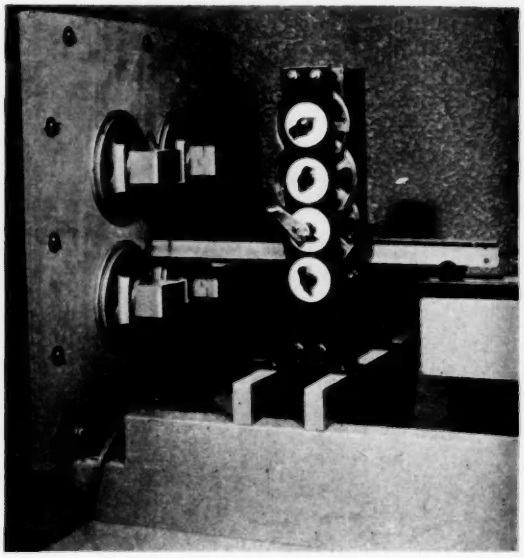


FIG. 6. View of source end of tube, showing mechanism for driving and measuring position of microphone.

mechanical noise which would otherwise interfere in the reading of pressure minima, and also eliminate binding in the motion of the microphone. The electrical equipment is normally placed adjacent to the desk shown in Fig. 4. An observer can therefore make all adjustments and readings for a complete run on one sample while remaining seated at the desk. It may also be noted that with a tube having as large a diameter as this, moving parts inside the tube do not have to be extremely small to avoid error due to effective change of tube cross section. Furthermore, the upper frequency limit of 1000 cycles is low enough that negligible distortion of the sound field is caused by a microphone of the size used.

The effects of attenuation along the length of the tube, due to absorption and radiation through the tube walls, must be taken account of in order to maintain satisfactory accuracy. As shown by Hall's analysis,[5] attenuation, provided it is small, causes a linear increase in the values of successive pressure minima with respect to distance from the sample, with negligible change in the values of the maxima, as shown in Fig. 7. The true pressure minimum is therefore obtained by extrapolating the observed values back to the position of the sample, it being unnecessary to know the value of the attentuation constant. If it is further assumed that the ratio D_1/D_2 is very nearly 0.5, then the observed values L' and L'' can be very easily corrected to the true value L by means of the chart in Fig. 8. In the present case, the largest errors due to attenuation occur at low frequencies, where for most materials the approximation $D_1/D_2 \doteq 0.5$ is most nearly true, so that the chart of Fig. 8 affords quite satisfactory accuracy.

The accuracy in measurement of L and D_1/D_2 required to obtain a given accuracy in impedance can be seen from inspection of Fig. 3 to vary rather widely and unpredictably over different

regions of the charts. Some information on this point can be gathered, however, from an analysis of the impedance values of a hypothetical sample. The values assigned to this sample are shown in Table I, and are representative of an "average" commercial acoustical material of 1″ thickness. Let us assume a desired accuracy of 1 point (an increment of 0.01) in the normal incidence absorption coefficient. From Fig. 2, this corresponds to an accuracy in L of 2 db at 100 cycles, and 0.2 db at 1000 cycles. The accuracy in impedance equivalent to a 1-point accuracy in absorption coefficient comes out to be 20 percent at 100 cycles, and 4 percent at 1000 cycles. These latter figures, in turn, correspond to an accuracy in the measurement of the distances D_1 and D_2 of about 2.5 mm at 100 cycles and 0.3 mm at 1000 cycles.

An idea of the fineness of control of the motion of the microphone necessary to locate and measure the pressure minima easily and accurately can be obtained from Fig. 9. Here the sound pressure near the minimum is plotted on a magnified scale in relation to the wave-length for two extreme values of absorption coefficient. In practice it is found that at low frequencies and low absorptions the positions of the minima can be easily determined, but that a fine, smoothly operating vernier adjustment is necessary to determine their values accurately. At high frequencies and high absorptions, the values of the minima are easily read, but curve width determinations are often necessary to locate their positions.

The above data give information as to the frequency stability required. Sudden fluctuations of the order of 0.1 percent would cause serious difficulty in locating sharp minima. A drift of about 0.3 percent between the times of measuring the first and second minima would produce an error in impedance equivalent to a 1-point increment in absorption.

Another important factor affecting the accuracy and especially the range of measurement is the purity of the test tone, since the maxima of the even numbered harmonics coincide with the minima of the fundamental. If it is desired, for example, to measure values of L as high as 40 db to an accuracy of 0.2 db, corresponding to a normal incidence absorption coefficient of 0.04, then the harmonic content must be at least 55 and preferably 60 db below the fundamental. The necessary filtering is usually accomplished by means of a frequency analyzer in the measuring circuit, although a set of low pass filters at intervals of an octave or less, having suitably sharp cut-off characteristics, is equally satisfactory and probably more convenient to use.

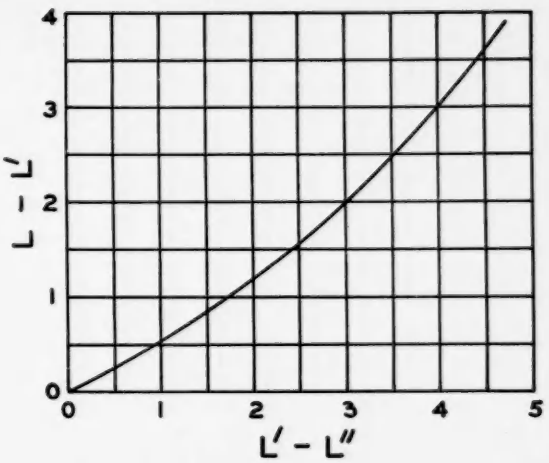


FIG. 8. Chart for determining true value of L from observed values, based on assumption that $D_1/D_2=0.5$.

TABLE I. Impedance and absorption values of a hypothetical acoustical material of 1″ thickness.

Frequency	$R/\rho c$	$X/\rho c$	α_n
100	3.0	−16.0	0.045
200	3.0	−8.0	0.15
500	3.0	−3.5	0.43
1000	3.0	−1.8	0.63

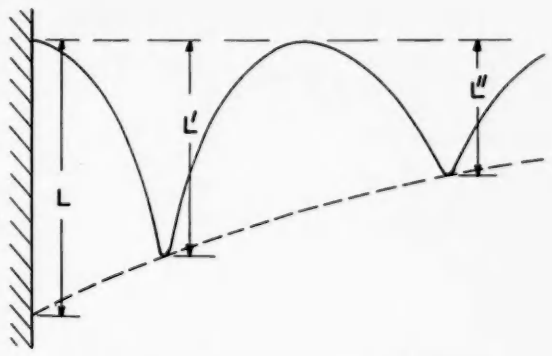


FIG. 7. Variation of pressure minima with distance from sample, due to attenuation along tube.

In conclusion, the writer wishes to express his

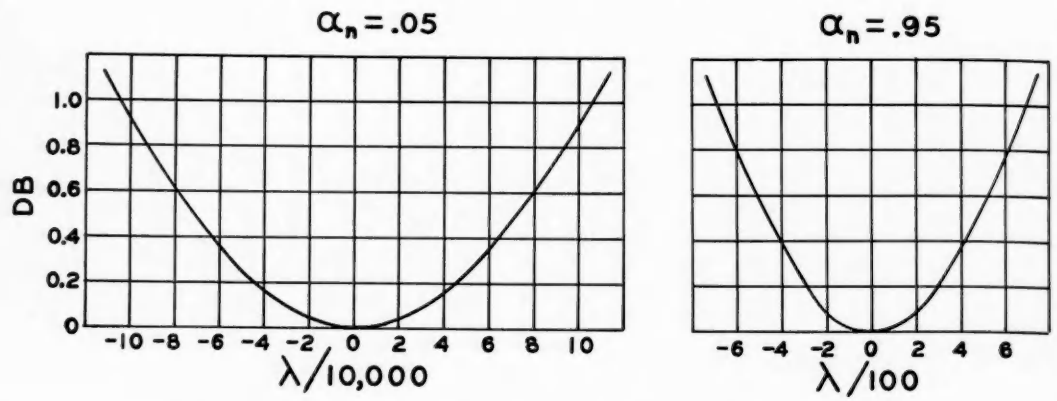


FIG. 9. Magnified plots showing sharpness of pressure minima for two values of normal incidence absorption coefficient.

appreciation of valuable advice and information offered by Professor William Hall, Mr. Paul Huber, Dr. Leo L. Beranek, and Dr. Richard H. Bolt.

Propagation of Sound Waves in the Atmosphere

B. GUTENBERG
California Institute of Technology, Pasadena, California
(Received August 31, 1942)

The effect of humidity on the velocity of sound waves is investigated (Eq. (5), Table I). The radius of curvature for a ray of sound which is propagated in the direction of the wind is given [Eq. (13)] and discussed. The amplitudes of sound waves as a function of the distance are given [Eq. (17)], and the relative importance of the quantities involved is discussed.

INTRODUCTION

THE problem of the propagation of sound waves in the atmosphere, though of practical interest, seems to have been somewhat neglected. The following article is a contribution to certain aspects of this problem.

SOUND VELOCITY IN HUMID AIR

It is usually stated in publications that the effect of humidity on the sound velocity is small. Assuming a purely adiabatic process, the sound velocity V in a gas is given by

$$V=(p\kappa/\rho)^{\frac{1}{2}}=(RT\kappa)^{\frac{1}{2}}, \quad (1)$$

where p = pressure, $\kappa=C_p/C_v$ is the ratio of the specific heats at constant pressure and at constant volume, ρ = density, R = gas constant for the given gas, and T = absolute temperature. For dry air $R=2.87\times10^6$ cm^2/sec.^{2} and $\kappa=1.4$ which gives

$$V=20.05\sqrt{T}(\text{m/sec.}). \quad (2)$$

For $T=273$°K, Eq. (2) gives $V=331.6$ m/sec. which is very close to the observed value 331.45.[1] For all temperatures to be expected in the atmosphere, the values calculated from (2) agree with the observations within the limits of error involved in the problems of this paper.

In humid air, ρ, R, and κ depend on the partial pressure h (sometimes called tension) of the water vapor. Using the index a for dry air, w for water vapor, and h for humid air, we find from (1)

$$V_h=V_a\left(\frac{\kappa_h}{\kappa_a}\frac{R_h}{R_a}\right)^{\frac{1}{2}}=V_a\left(\frac{\kappa_h}{\kappa_a}\frac{p}{p-\left(1-\frac{\rho_w}{\rho_a}\right)h}\right)^{\frac{1}{2}}$$
$$=V_a\left(\frac{\kappa_h}{\kappa_a}\frac{p}{p-0.38\,h}\right)^{\frac{1}{2}}. \quad (3)$$

With sufficient approximation[2]

$$\frac{\kappa_h}{\kappa_a}=\frac{(p-h)(\kappa_w-1)+h\frac{\kappa_w}{\kappa_a}(\kappa_a-1)}{(p-h)(\kappa_w-1)+h(\kappa_a-1)}=1-0.1\frac{h}{p-h}, \quad (4)$$

using $\kappa_w=1.3$ and $\kappa_a=1.4$. Introducing this result in (3) we find approximately

$$V_h=V_a+0.14\frac{h}{p}V_a=V_a+H, \quad H=0.14\frac{h}{p}V_a. \quad (5)$$

The correction H depends on the ratio of the partial pressure h of the water vapor to the pressure p (elevation above the ground). Near the ground, we may take as averages $p=760$ mm Hg, $V=340$ m/sec. and find with these figures approximately

$$H_0=0.063h \ (H \text{ in m/sec. } h \text{ in mm Hg}). \quad (6)$$

In Table I, calculated values for the approximate correction H_0 near the ground are given. In air with a relative humidity of x percent, the corrections must be multiplied by $x/100$. In warm, humid air, the corrections may exceed 1 percent of the value for dry air.

EFFECT OF WIND ON THE PATH OF SOUND WAVES

The equations for the paths of sound waves in the case that the wind direction forms an angle

TABLE I. Partial pressure h for temperatures t and approximate corrections H_0 to be added to sound velocity for dry air to find the sound velocity in air of 100 percent humidity near the ground. (Supposed $p=760$ mm Hg, $V=340$ m/sec. or $T=287$° K.)

t	+50	45	40	35	30	25	20	10	0	−10° C
h	92.5	71.9	55.3	42.2	31.8	23.8	17.5	9.2	4.6	2.1 mm Hg
H_0	5.8	4.5	3.5	2.7	2.0	1.5	1.1	0.6	0.3	0.1 m/sec.

[1] H. C. Hardy, D. Telfair, and W. H. Pielemeier, "The velocity of sound in air," J. Acous. Soc. Am. **13**, 226 (1942).

[2] E. Luebcke, "Schallgeschwindigkeit," *Handbuch der Physik* **8**, 626 (Springer, Berlin, 1927).

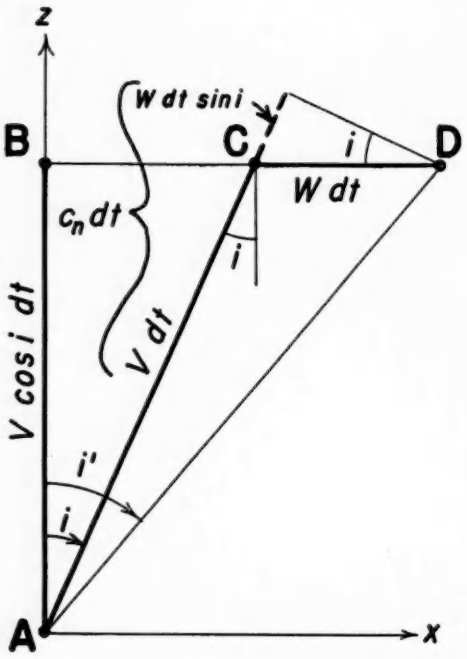


FIG. 1.

φ with the horizontal component of the sound path are too complicated[3,4] to be useful, even when it is assumed that the wind has no vertical component and that its direction does not change with height. Usually, the wind component ($W\cos\varphi$) is taken, and then the equations are applied which hold when the directions of the wind and of the sound waves are in the same vertical plane. However, it seems that even for this simpler case, no equations have been derived[5] which in general consider terms of the order W/V (W=wind velocity, V=sound velocity in still air). Complications arise mainly from the fact that the wave front connecting points with equal times of arrival of the waves is no longer perpendicular to wave paths. The sound velocity component normal to the wave front is $c_n = V + W\sin i$ (see Fig. 1). For c_n the usual law of refraction holds:

$$c_n/\sin i = \text{constant} = C = V/\sin i + W, \quad (7)$$

$$\sin i = V/(C-W). \quad (8)$$

From Fig. 1:

$$\tan i' - \tan i = (BD-BC)/AB = W/V\cos i, \quad (9)$$

or approximately $(i'-i)$ in radians $= W\cos i/V$. Thus, in applying Eq. (8) to i' instead of to i, an error of the order W/V is introduced, unless i is close to 90°.

The ray equation follows from Fig. 1:

$$x' = dx/dz = BD/AB = (V\sin i + W)/V\cos i. \quad (10)$$

The absolute value of the radius of curvature r is given by

$$r = \frac{(1+x'^2)^{\frac{3}{2}}}{x''} = \frac{\frac{1}{\cos^3 i}\left[1+2\frac{W}{V}\sin i+\left(\frac{W}{V}\right)^2\right]^{\frac{3}{2}} V^2\cos^2 i}{V^2\frac{di}{dz}+V\cos i\frac{dW}{dz}-W\cos i\frac{dV}{dz}+WV\sin i\frac{di}{dz}}$$

$$= \frac{V\left[1+2\frac{W}{V}\sin i+\left(\frac{W}{V}\right)^2\right]^{\frac{3}{2}}}{\frac{\cos i}{V}\left[(V^2+WV\sin i)\frac{di}{dz}+\cos i\left(V\frac{dW}{dz}-W\frac{dV}{dz}\right)\right]}.$$

Introducing from Eq. (8)

$$\cos i\frac{di}{dz} = \frac{(C-W)\frac{dV}{dz}+V\frac{dW}{dz}}{(C-W)^2} = \left(\frac{dV}{dz}+\frac{dW}{dz}\sin i\right)\frac{\sin i}{V} \quad (11)$$

[3] R. Emden, "Beiträge zur Thermodynamik der Atmosphäre," Meteorol. Zeits. **35**, 14, 74, and 114 (1918).
[4] B. Gutenberg, "Die Schallausbreitung in der Atmosphäre," *Handbuch der Geophysik* **9**, 89–144 (Gebr. Borntraeger, Berlin, 1932). P. Duckert, "Ueber die Ausbreitung von Explosionswellen in der Erdatmosphäre," Ergeb. d. Kosm. Physik **1**, 236–290 (1931). With 193 references.
[5] B. Haurwitz, "The propagation of sound through the atmosphere," J. Aer. Sci. **9**, 35 (1941).

gives

$$r=\frac{V\left[1+2\frac{W}{V}\sin i+\left(\frac{W}{V}\right)^2\right]^{\frac{1}{2}}}{\frac{dV}{dz}\left(\sin i-\frac{W}{V}\cos 2i\right)+\frac{dW}{dz}\left(1+\frac{W}{V}\sin^3 i\right)}. \tag{12}$$

The rays are concave towards the earth if the denominator is positive. Introducing the absolute temperature T from (2),

$$dV/dz=(10/\sqrt{T})(dT/dz),$$

$$r=\frac{V\left[1+2\frac{W}{V}\sin i+\left(\frac{W}{V}\right)^2\right]^{\frac{1}{2}}}{\frac{10}{\sqrt{T}}\left(\sin i-\frac{W}{V}\cos 2i\right)\frac{dT}{dz}+\left(1+\frac{W}{V}\sin^3 i\right)\frac{dW}{dz}}. \tag{13}$$

r=radius of curvature, T=absolute temperature, $V=20\sqrt{T}$ (sound velocity in still air), W=wind velocity, i=angle of incidence, z=elevation. For practical purposes, the numerator in (13) may be written:

$$V\left[1+\frac{W}{V}\sin i\right]^3 \quad \text{or} \quad [V+3W\sin i].$$

Usually dT/dz is negative. Writing $dT/dz=-\gamma$, $dW/dz=a$, the condition for a curvature of the rays concave toward the ground is given by

$$a\left(1+\frac{W}{V}\sin^3 i\right)>\frac{10\gamma}{\sqrt{T}}\left(\sin i-\frac{W}{V}\cos 2i\right). \tag{14}$$

For very flat rays (i near 90°), this leads to

$a>10\gamma/\sqrt{T}$; for example, for $T=289°$: $a>0.59\gamma$,

regardless of the elevation z. If the decrease of temperature (lapse rate γ) is about 6° per km, the wind must increase by more than 3½ m/sec. per km near the highest point of the ray to produce a return of the sound to earth. A wind increase of this order of magnitude had already been used in the early literature. It also has been pointed out that for our problem the changes in T and W with height are much more important than the absolute values of both quantities.

For $i=0$, (13) gives approximately

$$r=V/(a+W\gamma/2T). \tag{15}$$

If the temperature decreases with elevation, a straight ray directed vertically upward is possible only if the wind decreases with elevation in such a way that the denominator in (15) is zero. Usually this decrease need not exceed materially 1 percent of the wind velocity per kilometer.

AMPLITUDES OF SOUND WAVES THROUGH THE ATMOSPHERE

We suppose that there is no wind, and that sound waves produced at A in Fig. 2 start with the same energy in all directions within the small half-sphere. The energy between two cones formed by rays with angles of incidence i and $i+\epsilon$, respectively, is given by

$$a[\cos i-\cos(i+\epsilon)],$$

where a depends on the energy at the source and the radius of the sphere. The absorption on the path D (Fig. 3) is given to a first approximation

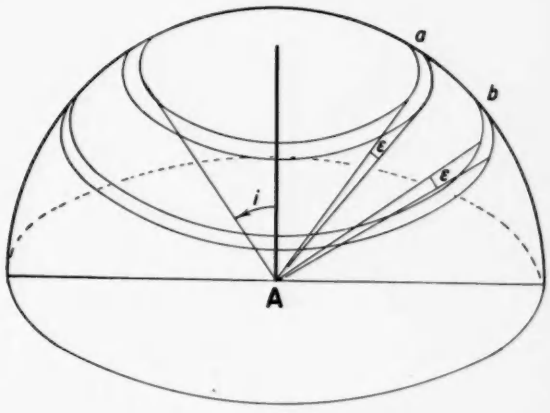


FIG. 2.

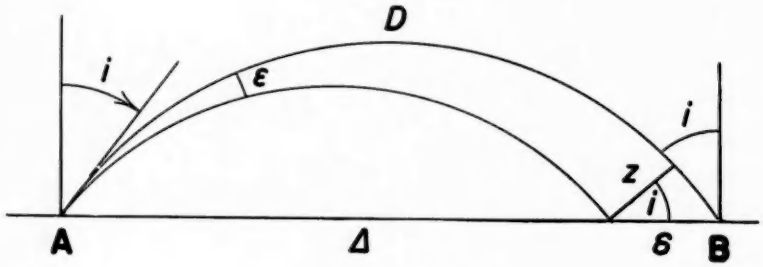


FIG. 3.

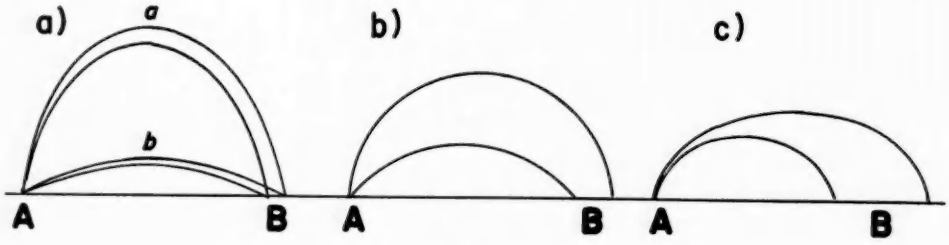


FIG. 4.

by e^{-kD}. The remaining energy arrives on a zone of area Z perpendicular to the rays:

$$Z=\pi[\Delta^2-(\Delta-\delta)^2]\cos i$$
$$=\text{approximately } 2\pi\Delta\delta\cos i.$$

Consequently, the energy flux at the distance Δ is given by

$$E=\frac{C[\cos i-\cos(i+\epsilon)]e^{-kD}}{\Delta\delta\cos i}, \qquad (16)$$

where C is a constant, depending on the original energy. As

$$\frac{\cos i-\cos(i+\epsilon)}{\delta}=\frac{d\cos i}{d\Delta}=-\sin i\frac{di}{d\Delta},$$

we find

$$E=Ce^{-kD}\frac{\tan i}{\Delta}\left(-\frac{di}{d\Delta}\right). \qquad (17)$$

E = energy flux, C = constant, k = absorption coefficient, D = length of sound path, i = angle of incidence, Δ = distance at the ground.

The factor $\tan i$ is partly a consequence of the fact that near the source less energy passes through a (Fig. 2) than through the larger zone b. Under otherwise equal conditions, waves along the path a (Fig. 4a) arrive at B with less energy than those over the path b. If $i=90°$, $\delta=\infty$, $di/d\Delta=0$.

The largest local changes are produced by $di/d\Delta$. If i changes rapidly with distance (Fig. 4b), much energy is concentrated near B. On the other hand, in Fig. 4c, it has been assumed that i changes slowly with Δ, the energy per unit near B is small.

To simplify the discussion we assume that the rays are circles (Fig. 5). Then

$$\cos i=\Delta/2r,$$
$$-\sin i(di/d\Delta)=[r-\Delta(dr/d\Delta)]/2r^2.$$

Neglecting the absorption factor, we have in this special case

$$E=\frac{C}{\cos i}\frac{1-\frac{\Delta}{r}\frac{dr}{d\Delta}}{2r\Delta}=C\frac{1-\frac{\Delta}{r}\frac{dr}{d\Delta}}{\Delta^2}. \qquad (18)$$

Equation (18) shows the expected decrease in energy with the square of the distance. The energy at a given point is especially large if the

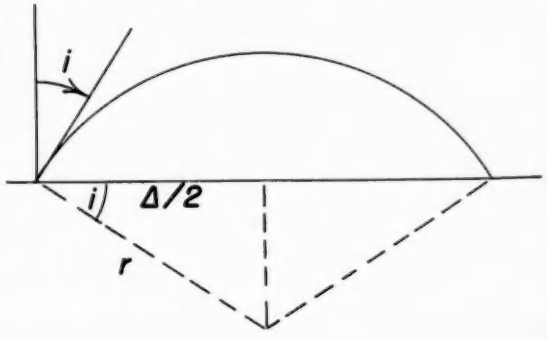


FIG. 5.

radius of curvature decreases rapidly with distance. According to Eq. (13) this requires that either the wind or the temperature or both increase rapidly with increasing height z in the region of the highest point reached by the sound waves. If this happens, sound waves from gun fire or explosions may be heard at unusually large distances.[6] On the other hand, the energy decreases considerably when the highest part of the rays enters a region where the radius of curvature increases rapidly.

As long as the rays remain below 20 or 30 km, the absorption factor e^{-kD} plays a smaller role for low tones ($\lambda > 10$ meters) than the change in the radius of curvature due to changes of wind and temperature with elevation. Approximately[7]

$$k = 33l/\lambda^2, \tag{19}$$

where l = mean free path of the molecules, λ = wave-length. If we assume a constant temperature of 273°K in the atmosphere, we find as a first approximation at the height h:

$$l = l_0 \frac{p_0}{p} = l_0 e^{h/8}, \quad k = 33 l_0 \frac{e^{h/8}}{\lambda^2}, \tag{20}$$

where the index zero refers to the ground, and h is measured in km.

Waves corresponding to the lowest audible tones ($\lambda = 20$ m) suffer an absorption of 1 percent per km at an elevation of about 60 km. At an elevation of 100 km, only about one-tenth of one percent of the energy of such waves arrives after traversing a distance of one km; for practical purposes the limit of propagation for the lowest audible sound waves over distances of 10 km or more is about at an elevation of 70 kilometers. From Eq. (20) it follows that for high tones (λ in meters) the corresponding elevations decrease roughly by 37 log $(20/\lambda)$ kilometers.

[6] B. Gutenberg, "The velocity of sound waves and the temperature in the stratosphere in southern California," Bull. Am. Meteorolog. Soc. **20**, 192 (1939). See especially Figs. 1 and 3, pp. 192 and 193.

[7] E. Schrödinger, "Zur Akustik der Atmosphäre," Physik. Zeits. **18**, 445 (1917). See also J. Kölzer, Meteorol. Zeits. **42**, 457 (1925).

Cancellation of the Electrical Cochlear Response with Air- and Bone-Conducted Sound*

KARL LOWY
University of Rochester, Rochester, New York
(Received August 1, 1942)

CONDUCTION of sound to the normal inner ear by bone is, from the physical point of view, much more complicated than that of propagation through air, because it involves a greater variety of mechanical processes. The question therefore arises, if the eventual stimulation of sensory elements within the cochlea is of the same nature for both types of hearing. Originally this was thought not to be the case. Bouman,[1] for instance, in an effort to explain certain observations on the so-called Broca phenomenon, advocated that the modes of inner ear vibration for air and bone conduction differ from each other, at least for certain positions of the bone receiver.

An argument in favor of the identity of physical events within the cochlea upon stimulation through air or bone was first given by Békésy.[2] He exposed a subject to a pure tone by air and bone conduction simultaneously. By adjusting intensity and phase he succeeded, under proper conditions, in making the tone disappear. Békésy's discovery was used by Bárány[3] for measuring the phase of bone-conducted sound. The fact that bone conduction is almost equally perceived by both ears rendered the experiments rather difficult so that Bárány had to deafen one ear with the aid of a noise apparatus. Although this by no means nullified the value of the experiments it might well have interfered with the accuracy of judgment of the person tested.

Wever and Bray[4] observed the similarity of intensity curves in the microphonic effect for both bone and air conduction, and assumed that in both cases the same receptors were stimulated. Although their experiments do not seem to offer an absolute proof, they are based on entirely objective methods. Békésy's and Bárány's results, on the other hand, appear quite conclusive but were obtained by a method involving the subjective impression of the person tested. It was therefore an obvious idea to try to establish the cancellation phenomenon by electrical methods in animal experiments.

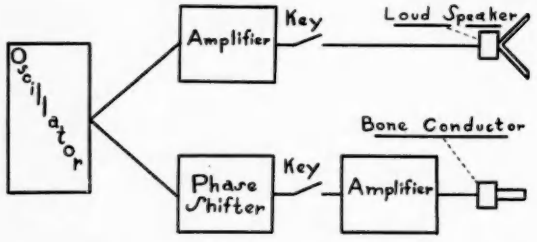


FIG. 1. Block diagram of sound system for extinction of cochlear potential.

METHOD AND RESULTS

Experiment 1: One pinna was removed and the bulla opened on five cats, anesthetized with nembutal. The outer meatus was connected with a loudspeaker by means of a tube. The tip of the bone-conduction unit, whose arrangement was described in a previous paper,[5] was put on the exposed bone above the meatus. Cochlear potentials were obtained from an active electrode, set on the promotorium posteriorly to the round

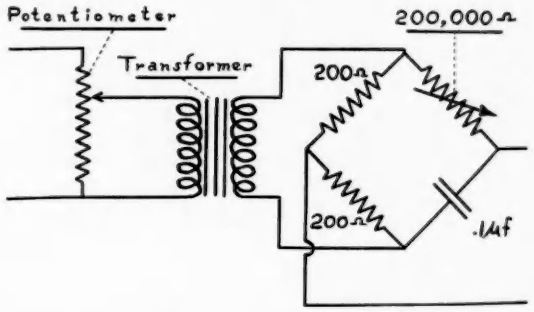


FIG. 2. Phase shifter.

* Communication No. 48, prepared under the direction of Elmer A. Culler, from the Animal Hearing Institute, Laboratory of Psychology. This Institute is maintained by aid of the Research Council, American Otological Society. This paper was read at the 1942 Meeting of the American Physiological Society (cf. Federation Proceedings, 1942, Vol. 1, p. 51).

[1] H. D. Bouman, Arch. Néerland. Physiol. **15**, 311 (1930).

[2] G. v. Békésy, Ann. d. Physik [5] **13**, 111 (1932); also Zeits. f. Hals-Heilk. **47**, 441 (1941).

[3] E. Bárány, Acta Otolar., Supplement 26 (1938).

[4] E. G. Wever and C. W. Bray, Ann. Otol. **45**, 822 (1936).

[5] K. Lowy, J. Acous. Soc. Am. **13**, 383 (1942).

window, the neutral electrode being connected with the skin of the neck. The potentials were amplified, filtered, again amplified, and visualized on a cathode-ray oscillograph for observation and photography.

Figure 1 shows a diagram of the sound system. The oscillator is of the beat frequency type. Two feedback amplifiers are used. The phase shifter is of the simplest construction and has been frequently described.[6] The potentiometer on the input side of the transformer (Fig. 2) controls the amplitude of the bone-conducted sound. The phase shifter permits a shift in phase of almost 180° for middle frequencies. Its range can be extended by simply changing the polarity of the output.

A pure sound was first conducted to the ear by air alone. The same sound was then administered by bone conduction alone, the potentiometer being adjusted so that the cochlear response, as observed on the oscillograph, was about equal in size to that obtained by air-borne sound. Both were then sounded together and the phase of bone-conducted sound shifted until minimal response was reached. A second adjustment of amplitude resulted in practically complete cancellation, as seen from Fig. 3, for three different frequencies. Once intensity and phase had been properly chosen the phenomenon could be demonstrated repeatedly without further manipulation as long as the bone conductor was left in place. The result was obtained regularly for all frequencies tested (250 to 3000 c.p.s.)

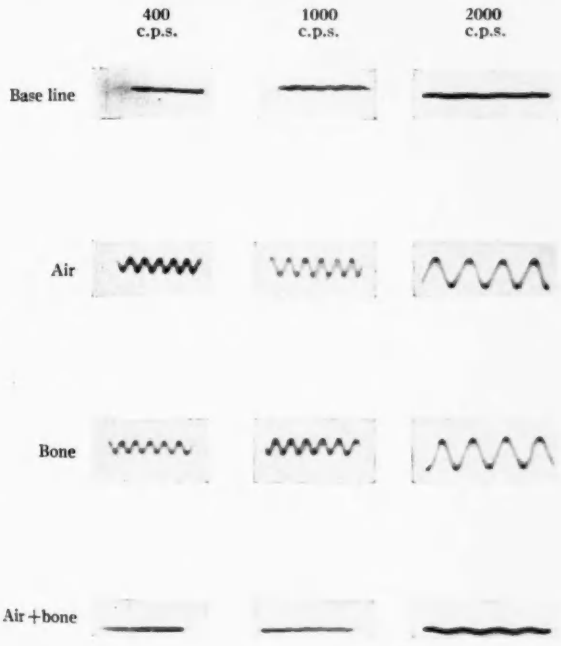


FIG. 3. Extinction of cochlear potentials in the cat.

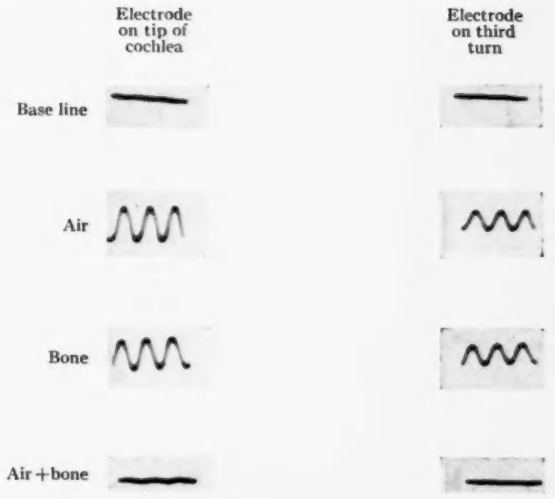


FIG. 4. Extinction of cochlear potentials in the guinea pig. One cochlea was destroyed. Bone conductor on opposite jaw. 600 c.p.s.

These experiments show that the sinusoidal electrical potentials generated in the cochlea by air- and bone-conducted sounds, respectively, can be made to cancel each other. But they do not justify the conclusion that both types of sound stimulation act on the same elements of the inner ear. This is easily seen from the following consideration. Assume for a moment that air- and bone-conducted sounds of the same frequency stimulate two different points within the organ of Corti. Each of these two points will emit an electrical response. If both sounds act together, the potential picked up from any point on the surface of the cochlea will be the algebraic sum of both voltages, modified, of course, by the impedance of the structures between stimulated point and place of pick-up. By adjusting amplitude and phase we should expect to be able to make the response disappear. However, if in this case the position of the active electrode be changed, the alteration in impedance should modify the pick-up and the electrical response should reappear. In other words, to prove that

[6] Cf. F. A. Everest, Electronics (Nov. 1941), p. 46.

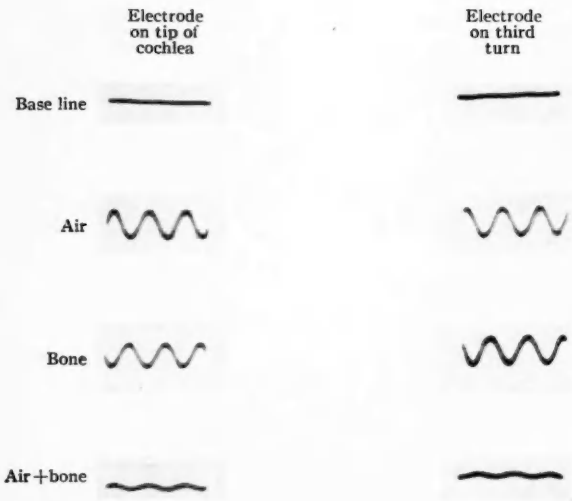


FIG. 5. Extinction of cochlear potentials in the guinea pig. One cochlea was destroyed. Bone conductor in midline of jaw, 2000 c.p.s.

disappearance of microphonics is actually due to extinction of vibration within the cochlea, it has to be shown that the phenomenon is independent from the position of the active electrode. This was done in the following experiment.

Experiment 2: In nine guinea pigs, anesthetized with urethane, one bulla was opened. The outer ear was connected with a loudspeaker by a tube, and the bone conductor attached to the exposed lower jaw. Two tungsten wires, serving as active electrodes, were put on the cochlea, one close to the tip, the other one on the third turn. Bone- and air-conducted sounds were applied to the ear, the wire on the tip first being used as the active electrode. Cancellation was obtained in the usual way. Hereafter, everything being left unchanged, the other wire was used as the active electrode. Cancellation was found to be still present, and could be demonstrated after repeated shifts from the tip electrode to that on the base of the cochlea. The phenomenon was found throughout the frequency range tested, namely, 250–3000 c.p.s. (Figs. 4 and 5).

Although different positions of the bone receiver must involve different modes of bone vibration, the cancellation phenomenon occurred independently from the place of application of the bone conductor. Thus, in the experiment in Fig. 4, the receiver was connected with the opposite angle of the jaw, whereas in Fig. 5 cancellation was obtained with the bone conductor in midline.

At first, all experiments were done with one cochlea destroyed. Later, it was seen that this precaution was unnecessary. The potential due to stimulation of the other ear by bone conduction apparently does not spread sufficiently to interfere with the result obtained.

It might be added that quantitative measurements of the phase of the electrical response could be obtained with a calibrated phase shifter.

SUMMARY

1. Mutual cancellation of cochlear potentials due to air- and bone-conducted sounds, respectively, can be obtained within a wide frequency range.

2. Once cancellation has been established, the phenomenon is independent from the site of the active electrode on the cochlea. These results support the assumption that tones, reaching the inner ear by bone conduction, stimulate the same elements as do air-conducted tones of equal frequency.

3. Extinction of the cochlear microphonics can be obtained for various positions of the bone receiver.

An Experimental Study of Subjective Tones Produced Within the Human Ear

CHESNEY R. MOE*
Department of Physics, University of Southern California, Los Angeles, California
(Received March 15, 1942)

Quantitative measurements are reported on the intensities of subjective tones produced within the human ear under single and dual tone excitation. The measurements are made by the exploring tone method. The even and odd subjective harmonics show some differences, indicating that the organ, or set of organs, producing non-linearity is not the same as the source of asymmetry. The intensities at which these two distorting effects first appear are not the same. The subjective summation tones are, in general, weaker than the corresponding difference tones of the same order. These differences are to be expected if auditory masking is a process occurring within the hearing mechanism.

THE problem of the existence, nature, and explanation of subjective harmonics and combination tones has been a controversial one for the past two centuries. Recent investigations have shown that when a single sinusoidal sound wave strikes the hearing mechanism, the ear perceives not only the fundamental, but a series of harmonics of the fundamental as well. The fact that these harmonics may be partially masked by the fundamental and consequently may be difficult to detect does not detract from their actual existence in the hearing process. These harmonics are attributed to a lack of linearity of response within the ear itself and are termed *subjective harmonics*. If two or more sinusoidal sound waves simultaneously impinge upon the hearing mechanism, each tone will set up its own series of harmonics. In addition to these harmonic tones, a series of *subjective summation* and *subjective difference* tones can be detected. A summation tone has a frequency equal to the sum of the frequencies of the fundamental tones or to the sum of the frequencies of any combination of their respective harmonics. A difference tone has a frequency equal to the difference between the frequencies of the fundamentals or to the difference between the frequencies of any combination of their respective harmonics. These tones are frequently referred to as *combination tones*.

Difference tones were discovered as early as 1714 by Tartini.[1] Up to the middle of the nineteenth century it was believed that the difference tone was simply a beat tone. Lagrange and Young, investigating these tones, did much to advance this explanation of the existence of the observed tones. Helmholtz,[2] in 1856, observed what he termed as a "summational" tone having a frequency equal to the sum of the frequencies of the two primary tones striking the ear and felt that the beat tone theory was inadequate to explain the existence of this summation tone. Accordingly, he formulated a theory based upon the non-linearity of the medium transporting the sound waves and on this basis was able to predict the existence of the observed difference and summation tones. Koenig,[3] leading a group of workers who differed in their ideas from those proposed by Helmholtz, did not admit the existence of the summation tone and hence subscribed to the beat tone theory. Koenig attributed the tone that Helmholtz had classed as a summation tone to be actually a difference tone between partials of higher order. Considerable investigation was undertaken by many workers attempting to settle this controversy.

In 1924, Wegel and Lane,[4] as a part of a study on masking, identified a large number of combination tones, recognizing at least 19 separate subjective tones produced by the simultaneous action of the two frequencies, 700 and 1200 cycles, respectively. They did not report measure-

* Now in the Department of Physics, San Diego State College, San Diego, California.

[1] A. T. Jones, "The discovery of difference tones," Am. Phys. T. **3**, 49–51 (1935).

[2] H. L. F. von Helmholtz, *On the Sensations of Tone*, translated by A. J. Ellis (Longmans, Green and Company, New York, 1912), pp. 156 and 411.

[3] R. Koenig, *Quelques Experiences d'Acoustique* (Paris, 1882), pp. 89 ff.

[4] R. L. Wegel and C. E. Lane, "The auditory masking of one pure tone by another, and its probable relation to the dynamics of the inner ear," Phys. Rev. **23**, 266–285 (1924).

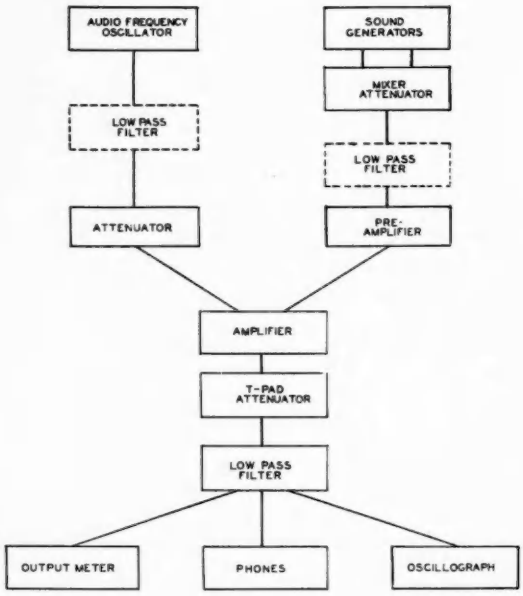


FIG. 1. Arrangement of experimental apparatus.

ments upon the intensities of these combination tones. Fletcher[5] reported some work performed by himself and Graham on the intensities of the subjective harmonics of certain fundamental tones, but made no mention of the frequencies used in the work. Cotton[6] has reported the identification of a number of combination tones between the unison and the octave for a 1000-cycle note.

The present study was made primarily to determine the intensities of the various combination tones developed within the human ear under single and dual tone excitation. If the ear faithfully obeyed Hooke's law, in which case the auditory response would be directly proportional to the exciting stimulus, an equation of the following form would be sufficient completely to identify the relationship between the pressure p of the sound wave at the tympanic membrane and the cochlear response R generated within the ear:

$$R=kp,$$

where k is a constant. Since deviations from linearity are known to occur within the hearing mechanism, an equation of the following type might satisfactorily represent the manner in which the cochlear response and the exciting sound pressure are related:

$$R=A_1p+A_2p^2+A_3p^3+A_4p^4+A_5p^5+\cdots, \quad (1)$$

where A_1, A_2, A_3, etc., have values dependent upon the degree to which the ear deviates from linearity and symmetry. If the ear is excited by a single sinusoidal sound wave, the instantaneous sound pressure p is determined by the following relationship:

$$p=p_0\cos(2\pi ft), \quad (2)$$

where p_0 is the maximum value of the pressure of the sound wave and f is the frequency of the sound source. Substituting this pressure relationship into Eq. (1) provides an equation containing terms which can be expanded by well-known trigonometric forms. After expansion, a relationship is obtained involving the fundamental frequency f and a series of terms containing higher harmonics, $2f$, $3f$, etc., above the fundamental, in addition to a constant displacement term. Fletcher[7] has derived the coefficients of these harmonic terms as far as the third harmonic.

Equation (1) may be utilized to predict the production of combination tones. If two sinusoidal sound waves actuate the ear at the same time, the resultant sound pressure may be represented by the relationship:

$$p=p_1\cos(2\pi f_1t)+p_2\cos(2\pi f_2t), \quad (3)$$

where p_1 and p_2 are the sound pressure amplitudes and f_1 and f_2 are the frequencies of the two sound sources, respectively. Upon substituting Eq. (3) into Eq. (1), expanding the terms and substituting suitable trigonometric forms, an equation is obtained in which terms involving the harmonics of each of the two primary frequencies are obtained. In addition, terms involving the summation and difference frequencies, of the form $(f_1\pm f_2)$, $(2f_1\pm f_2)$, $(f_1\pm 2f_2)$, $(2f_1\pm 2f_2)$, etc., are obtained. Cotton[6] has derived the coefficients of these terms as far as the seventh power of the pressure.

The intensity of each of the subjective tones produced in this study was determined by what has been called the "best beat note" method.

[5] H. Fletcher, "A space-time pattern theory of hearing," J. Acous. Soc. Am. **1**, 311–343 (1930).

[6] J. C. Cotton, "Beats and combination tones at intervals between the unison and the octave," J. Acous. Soc. Am. **7**, 44–50 (1935).

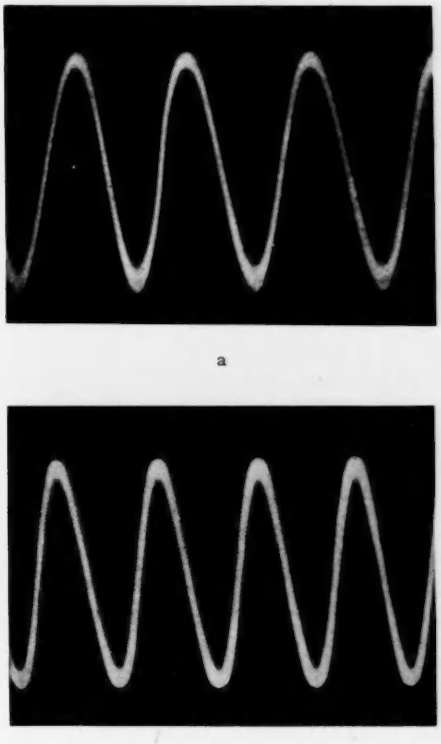
[7] H. Fletcher, *Speech and Hearing* (D. Van Nostrand, New York, 1935), p. 312.

This procedure has been used by Wegel and Lane,[4] Fletcher,[5] Cotton,[6] and v. Békésy.[8] The procedure consisted essentially in having an exploring tone introduced into the output signal in addition to the fundamental tones. When the frequency of the exploring tone was adjusted to be nearly equal to the frequency of any of the subjective tones developed within the ear, beats were heard between the subjective tone and the exploring tone. As the intensity of the exploring tone was altered, the beat note envelope possessed varied amounts of modulation. When the beats were considered as most pronounced, the intensity of the exploring tone was taken as equal to the intensity of the subjective tone under test. It was found that a frequency of approximately 2 or 3 beats per second was most satisfactory for the ear to follow the change in intensity of the beat note.

The sound sources used in this work consisted essentially of a coil formed on a strong fixed permanent Alnico steel magnet, which in turn was placed in the proximity of a rotating steel gear. One gear and one magnetic pick-up were needed for each desired frequency. The permanent magnet was cylindrical, approximately $\frac{1}{4}$ inch in diameter, with a knife edge ground on one end. A 500-turn coil was formed near the knife edge end of the magnet. Frequencies of approximately 690 and 950 cycles, respectively, were produced by this generating system. From the generator the sound signals were transmitted through a mixer, a low pass filter, and a preamplifier. At this point the generated signal was coupled to a signal from a variable beat frequency audio-oscillator. The combined signal next was carried through a three-stage amplifier and an attenuator, from which it could be sent into any one of three instruments; a crystal headphone, a cathode-ray oscillograph, or an output meter. Figure 1 shows the arrangement of experimental apparatus. Only one unit of the headphone assembly was used in order that monaural measurements could be made. The headphone was provided with a sound pressure calibration curve made by the manufacturer, enabling one to determine the sound input intensity striking the ear.

An harmonic analysis of the wave form produced by each of the two primary tones was made at an intensity level of 110 db for each primary tone. This intensity level was equal to the maximum intensity used during the experimentation. The second harmonic had an average intensity level of approximately 36 db below the intensity level of the primary tone. The remaining harmonics showed intensity levels at least 40 db below the primary intensity level. Oscillograms showing the wave forms of the two sound signals are given in Fig. 2.

Before each set of readings was taken, the intensity level of the desired primary tone was adjusted to a satisfactory value, accomplished with the aid of the calibration curve for the headphone. The observer next was permitted to adjust the frequency and intensity of the oscillator signal until he judged the beat note as possessing a maximum amount of modulation. After this most pronounced beat note was obtained, the intensity of the exploring tone was found by determining, with the attenuator, the



a

b

FIG. 2. Wave forms of the generated tones. (a) 690 cycles; (b) 950 cycles.

[8] G. v. Békésy, "Über die nichtlinearen Verzerrungen des Ohres," Ann. d. Physik **20**, 809–827 (1934).

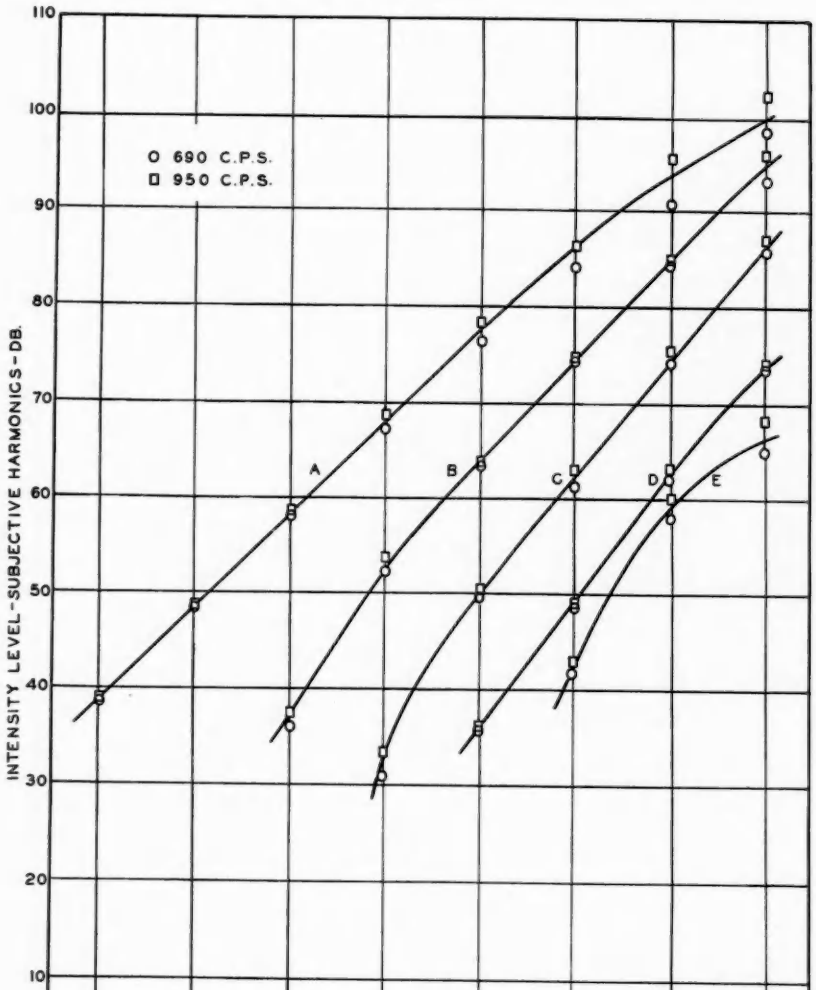


FIG. 3. Mean values of the intensity levels of the first five subjective harmonics from the two frequencies, 690 and 950 cycles, respectively. *A*, first harmonic; *B*, second harmonic; *C*, third harmonic; *D*, fourth harmonic; *E*, fifth harmonic. 0 db = 0.0002 dynes per sq. cm.

number of decibels that its intensity was below the intensity of the primary tone. Sufficient rest periods were provided in order to reduce the fatigue and hysteresis of the ear to a minimum.

The intensities of the subjective harmonics obtained from each of the two frequencies, 690 and 950 cycles, respectively, were determined by the method discussed above. The primary tones were presented to each ear of three observers having normal hearing. A total of 110 readings was made at each intensity level. Figure 3 shows the mean values of the intensity levels of the first five harmonics from each of the two primary frequencies. The intensity levels of the subjective harmonics are plotted as a function of the intensity level of the primary tone striking the observer's ear. The first harmonic had an intensity very nearly equal to that of the primary tone until an intensity level of about 70 db was reached. For higher intensities the first harmonic

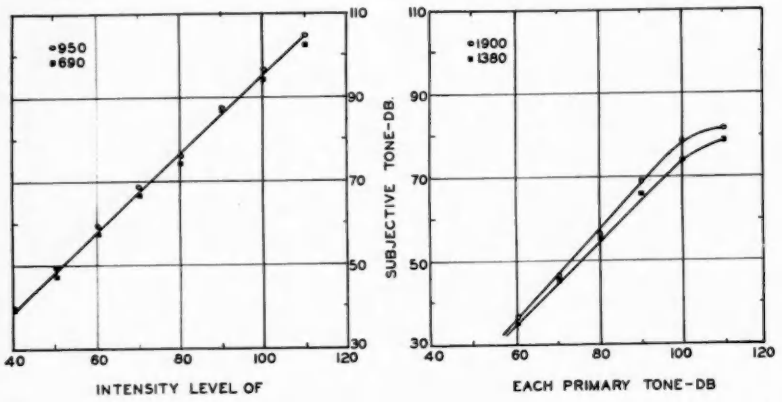
gradually decreased with respect to the primary tone. The general form of the intensity curves of the other four harmonics was similar to that of the first harmonic except that each harmonic was progressively weaker than the previous one. No harmonic, except the fundamental, was measurable when the intensity level of the primary tone was below 50 db. These curves show considerable similarity to generalized curves produced by Fletcher.[5] Fletcher has stated that the distortion produced within the hearing mechanism is dependent upon the physical intensity level of the impressed sound rather than upon its sensation level. The second, third, and fourth harmonics tended to bear out this hypothesis since the intensity curves of these harmonics from the two primary tones were very nearly equal. For the first and fifth harmonics, some divergence existed between the harmonics of the two primaries, especially when the intensity level of the primaries was high. In view of the magnitude of the probable errors of the readings, sufficient divergence did not exist to invalidate the hypothesis.

An additional experimental investigation was made into the nature of combination tones perceived when two sound sources simultaneously impinged upon the ear and the frequency and intensity of each combination tone were determined by the best beat note method. The intensity level of each of the primary tones was kept equal during the experimentation and at least 60 readings were taken at each intensity level. Figure 4 shows the intensity level of the respective subjective tones developed as a function of the intensity level of the primary tones.

An observation of the subjective harmonics shows characteristics similar to the harmonics obtained from a single source. The intensity of the odd harmonics increased practically linearly with the intensity level of the primary tones, while the even harmonics tended to level off at the higher primary intensities. This fact was not borne out in the measurements on the subjective harmonics from a single frequency source. It is recognized, however, that no conclusive evidence is presented relative to this point to make a definite statement since there is a lack of readings at the very high intensity levels. It is interesting, on the other hand, to note that Stevens and Newman,[9] in their investigations on the cochlear microphonics from a cat's ear, when stimulated by a pure tone of 1000 cycles, have found that the odd and even harmonics behave quite differently. They found that at the higher intensity levels, the odd harmonics reached a maximum intensity and remained relatively constant thereafter. The even harmonics reached a maximum intensity, then decreased in intensity as the intensity level of the primary tone was continually raised. These results, as meager as they are, tend to show that the mechanism within the ear producing nonlinearity acts in a different manner from the organ, or set of organs, producing asymmetry. The breakdown of the two distorting effects apparently occurs at different intensity levels.

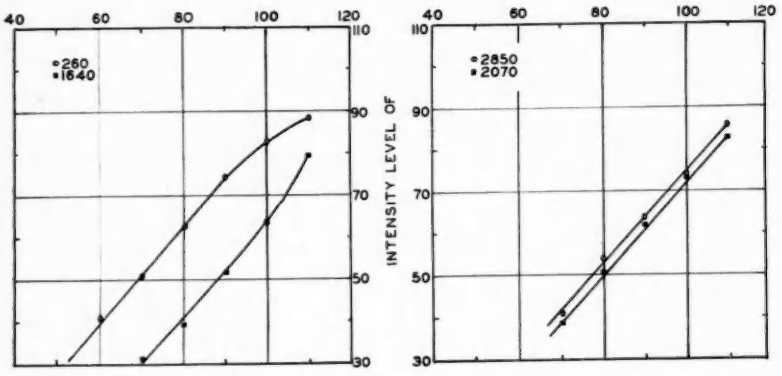
The summation and difference tones showed considerable variability. In practically all cases the summation tone was less intense than the corresponding difference tone of similar order. For the summation and difference tones which were widely different in frequency, the difference in intensity was generally quite large, although the differences tended to decrease at the higher intensity levels. The higher order tones appeared to be more nearly equal in intensity than did the lower order tones. Auditory masking quite likely accounted for much of these differences. A tone of a frequency much below that of a masking tone is not perceptibly masked for lower intensities and only slightly masked at the higher intensities. A tone of frequency much higher than the masking tone is not perceptibly masked for the lower range of intensities, but the masking becomes very pronounced when the intensity level of the masking tone is increased.[4] This factor of masking, however, did not affect the experimental measurements made on the combination tones, since the exploring tone, being practically equal in frequency to that of the combination tone under investigation, was subjected to a similar condition of masking as the combination tone and as a consequence the intensity of the exploring tone could be considered equal to the subjective tone intensity at the point of the most pronounced beat note.

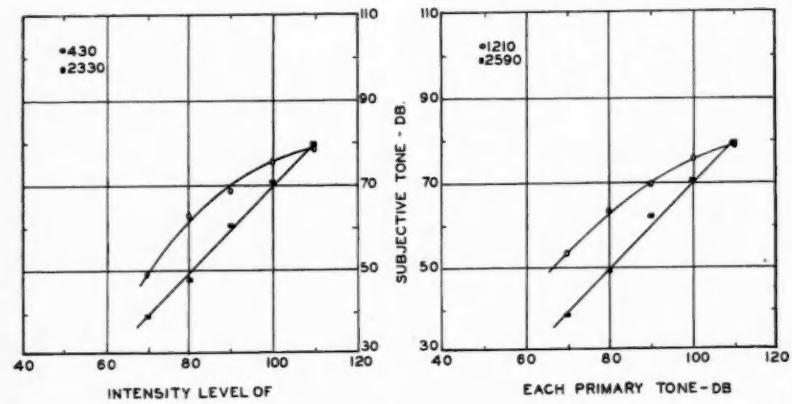
[9] S. S. Stevens and E. B. Newman, "On the nature of aural harmonics," Proc. Nat. Acad. Sci. **22**, 668–672 (1936).



a

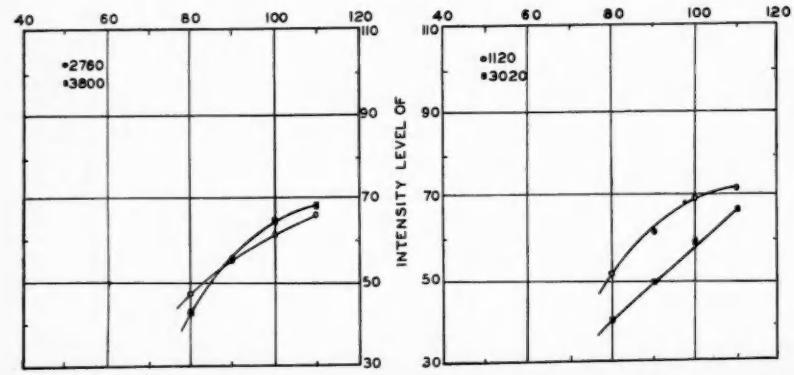
Frequency	Combination tone	Frequency	Combination tone
690	f_1	1380	$2f_1$
950	f_2	1900	$2f_2$
260	f_2-f_1	2070	$3f_1$
1640	f_2+f_1	2850	$3f_2$

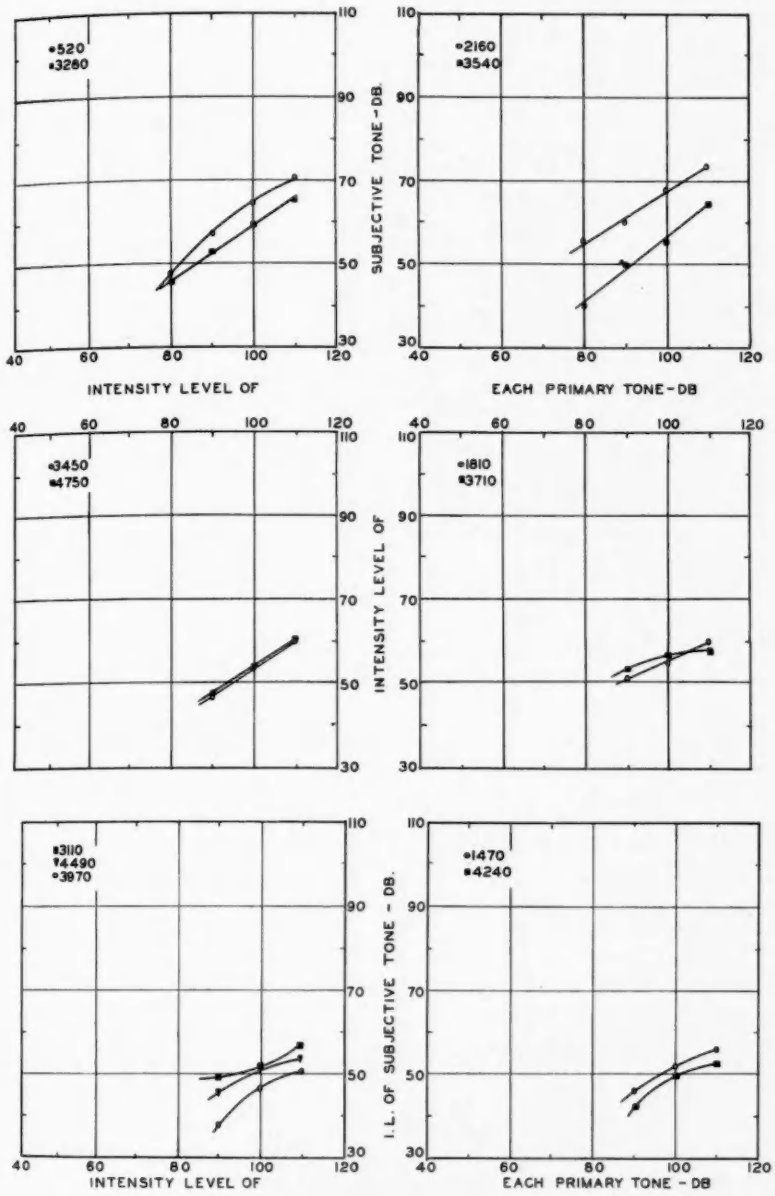




b

Frequency	Combination tone	Frequency	Combination tone
430	$2f_1-f_2$	1210	$2f_2-f_1$
2330	$2f_1+f_2$	2590	$2f_2+f_1$
2760	$4f_1$	1120	$3f_1-f_2$
3800	$4f_2$	3020	$3f_1+f_2$





c

Frequency	Combination tone	Frequency	Combination tone
520	$2f_2-2f_1$	2160	$3f_2-f_1$
3280	$2f_2+2f_1$	3540	$3f_2+f_1$
3450	$5f_1$	1810	$4f_1-f_2$
4750	$5f_2$	3710	$4f_1+f_2$

d

Frequency	Combination tone	Frequency	Combination tone
3110	$4f_2-f_1$	1470	$3f_2-2f_1$
4490	$4f_2+f_1$	4240	$3f_2+2f_1$
3970	$3f_1+2f_2$		

FIG. 4. Mean values of the intensity levels of subjective combination tones from a dual frequency source, containing the frequencies 690 and 950 cycles. Frequencies are indicated in upper left-hand corner of each graph.

Wever, Bray, and Lawrence[10] have discovered that interference appears in the electrical activity of the cochlea as a reduction in the magnitude of the response to a given tone when a second tone is sounded simultaneously. This effect is distinctly different from the masking effect. Cochlear interference occurs between tones of any frequency while masking is limited to frequencies in the region of the masking tone and its harmonics. No results are given to show the magnitude of this tonal interference in human ears and only limited data are available on animal experimentation. If this effect is present to any appreciable extent in human hearing, there is considerable likelihood that such interference factors

[10] E. G. Wever, C. W. Bray, and M. Lawrence, "The interference of tones in the cochlea," J. Acous. Soc. Am. 12, 268–280 (1940).

may contribute to the differences noted between difference and summation tones of similar order.

This work did not take into consideration any effect of phase on the nature of the subjective tones. Investigations have shown that at high intensities the phase relations between the subjective harmonics can alter the tonal quality and loudness of the resultant sound. Chapin and Firestone[11] have found that when relatively loud second harmonics are added to a loud primary tone, the over-all loudness was dependent upon the relative phase angles between the primary tone and second harmonic. Trimmer and Firestone[12] found that the timbre of a complex wave was dependent upon the relative phases of the components, provided the fundamental was a low pitch tone. Lewis and Larsen[13] noted that perceptible changes in the loudness of a difference tone occurred when the relative phases of the primary frequencies were altered. Considerable additional work needs to be done on this phase effect and an extension of this present study is to be made in this field.

Due to the generation of subjective tones from the many frequencies in ordinary speech, a complex auditory sensation may be experienced which tends to complicate the auditory pattern and cause a lack of clarity in the recognition of speech, especially at the higher intensity levels.

The author wishes to take this opportunity to express his appreciation to Dr. Arthur W. Nye, whose supervision and kindly counsel have been extremely valuable and encouraging.

[11] E. K. Chapin and F. A. Firestone, "Influence of phase on tone quality and loudness," J. Acous. Soc. Am. **5**, 173–180 (1934).

[12] J. D. Trimmer and F. A. Firestone, "An investigation of subjective tones by means of the steady tone phase effect," J. Acous. Soc. Am. **9**, 24–29 (1937).

[13] D. Lewis and M. J. Larsen, "Cancellation, reinforcement, and measurement of subjective tones," Proc. Nat. Acad. Sci. **23**, 415–421 (1937).

Acoustical Society News

0.05 V/A in Practice

A certain member of the Acoustical Society recently lost from his acoustical materials installation crew a young Italian laborer who was drafted into the Service. The following report has been received from the lad concerning the use of absorbing material in the army camp.

". . . It is very hot here. the soldier use salt tablets 4 or 5 time a day. Soldier pass out every day. There are 30,000 Soldiers here from all over the Country. from day to day, soldiers are shipped to other camps and oversea.

"The Colonel ask me over to the Camp Radio Studio to treat it for Sound. It is a one room Bungalow, used for remote Control.

"I put on an act that I was not sure what to do but figured out all hard surfaces. leakes in the sash and flooring there was no rug. I had them pad the ceiling with soft material sealed all windows used a rug from wall to wall padded all the walls and prayed. Every thing panned out. he is tickled pink. with my system. I couldn't miss. that was a break.

"I am thanking you from the bottom of my heart for giving me the chance of working with acoustical material. . . ."

New Members

Victor Maurice Bernin
1639 Catalpa Street
Chicago, Illinois
Electrical Inspector
Western Electric Company, Inc.
208 West Washington Street

George Leon Bonvallet
1718 West 71st Street
Chicago, Illinois
Engineer, Burgess Battery Company

William Smith Cramer
121 Power Street
Providence, Rhode Island
Research Assistant, Department of Physics
Brown University

Robert D. Elbourn
1600—31st Street, S. E.
Washington, D. C.
Electrical Engineer
Naval Ordnance Laboratory

Price E. Fish
30 Fitch Avenue, New London, Connecticut
Research Engineer
Columbia University
New London, Connecticut

Galen McKee Glidden
133 North Sacramento Boulevard
Chicago, Illinois
Safety Engineer
E. D. Bullard Company

Neuzat Ismail Gürbüz
1309 Washienaw Avenue
Ann Arbor, Michigan
Student, University of Michigan

Hayward Webb Henderson
112 Hammond Road, Belmont, Massachusetts
Special Research Associated
Harvard Underwater Sound Laboratories

Robert L. Hoyle
2815 West Roscoe Street
Chicago, Illinois
Engineer, Burgess Battery Company

Eugene Tsung-yueh Hsu
Physics Department, Brown University
Providence, Rhode Island
Graduate Student

F. Edgar McGee
465 Washington Street, Buffalo, New York
Secretary, National Noise Abatement Council

William F. Waldrop
1508 Vineville Avenue, Macon, Georgia
Professor of Music Education
Conservatory of Music
Wesleyan College

William Layne Woolf
Stevens Institute of Technology
Hoboken, New Jersey
Research Engineer

Matthew E. Zaret
3961—48th Street, Long Island City, New York
Research Engineer, Sonotone Corporation
Elmsford, New York

Paul R. Wischnef
Department 817, Sears, Roebuck and Company
925 South Homan Avenue
Chicago, Illinois
Chief Engineer

Resigned: Donald A. Laird (Fellow), Charles L. Badley, William C. Hyatt, Edna Carter (Members)

Deceased: M. A. Goldstein (Fellow), Theodore Cassebeer (Member)

Transferred to Fellowship: Hale Sabine, Vincent Salmon

Fellows	166
Members	679
Total membership	845

Current Publications on Acoustics

Book Review

Practical Acoustics and Planning Against Noise. HOPE BAGENAL. Pp. 140+x. Chemical Publishing Company, Brooklyn, New York, 1942. Price $2.50.

The aim of the author has been "to provide a short handbook useful during an interim period when libraries and works of reference are fewer and less accessible than formerly." In line with its purpose, the book contains little theoretical treatment of sound problems, and is devoted largely to means for realizing in practice the knowledge that the research of the last twenty-five years has supplied. It is interesting to note the shifting of emphasis from the older problem of auditorium acoustics to the much more universal problem of providing reasonably quiet living and working conditions for people generally. The first half of the book is devoted largely to practical measures of design and construction that will serve to abate the noise nuisance in living space. In the list of illustrations one finds detailed drawings under such captions as "Plan for quiet bed-sitting room flats," "Partitions for working class flats," "Sound insulation at party walls," "Insulation of wood floors," etc. Throughout, the author is quite aware of the noise problems of low cost living, when light, cheap construction, and the close packing of the occupants makes these problems of major importance to health and well being. Particularly suggestive for the designer of apartment houses are the layouts of adjacent apartments so that the noisy portions of one are not directly contiguous to rooms in the other where quiet is particularly desirable.

Common sense preventive planning will go a long way toward obviating the necessity for brute force methods of wall insulation, which are expensive and frequently ineffective.

It is significant to note the frequent references to reports from the British Ministry of Health and the Noise Abatement League. Mr. Bagenal is an English architect who for a great many years has been deeply interested in the practical aspects of architectural acoustics, and his handbook is written against a background of sound technical training and years of actual experience. The architect or builder, conscious of noise abatement as one of the problems of building design, will be well served by a careful reading of his book. It would appear that governmental agencies in England have given much more attention to the control of noise as a health measure than has been the case in this country. *Practical Acoustics* passes on in concise and useful form the results of this work.

The second half of the book, devoted to the acoustical design of auditoriums, contains less that will be new to the informed reader in America. It does, however, bring out the importance of architectural design as a factor in the acoustical properties of audience rooms, the distinction between useful reflection of sound and the deleterious effects of reverberation and echo. Written by an architect, it should appeal to the practical designer. The point of view presented should help to correct the all too prevalent tendency among architects to ignore acoustic considerations in design, leaving the solution of acoustical problems to the use of absorbent treatment. There is plenty of evidence that an auditorium or concert hall may meet the requirements of proper reverberation, and still be acoustically unsatisfactory.

Without subscribing to all of the author's conclusions regarding the acoustical treatment of concert halls and broadcasting studios, one can still be grateful for the considered opinions offered on this still mooted question. The tradition of the acoustic virtues of wood paneling is one which deserves respect, if for no other reason than that of its great age. But to ascribe the acoustic excellence of the Leipzig Gewandhaus to its 5000 square feet of paneling, "kept rubbed," is to ignore the quantitative aspects of the matter, as well as the fact that plenty of equally good halls of modern fire-proof construction are to be found. It is difficult to see how a "large area of wood with a glossy finish" can give "a brightness of tone" that might not equally be ascribed to a painted hard plaster surface. The acoustic virtue of wood, in this reviewer's opinion, is limited to its use in the floor and walls of an orchestral stage, when its forced vibration from the immediate contact with the 'cellos and double basses reinforces the lower rather than the upper registers of the orchestra.

Taken as a whole, *Practical Acoustics* admirably carries out the aim of its author in giving in concise and usable form the results of modern acoustical science as they apply to building problems. Due to the use of rather fine print, it is a longer book than its 140 pages would indicate. One might suggest that its contents deserve a better job of bookmaking than the publishers have done.

PAUL E. SABINE
Harvard Underwater Sound Laboratory

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